1990

Comparing the time efficiency of several timber inventory designs

William L. Wood
The University of Montana

Comparing the Time Efficiency of Several
Timber Inventory Designs

By

William Louis Wood

B.S. University of Montana, 1982

Presented in partial fulfillment of the requirement

for the degree of Master of Science

UNIVERSITY OF MONTANA

1990

Approved by:

Chairman, Board of Examiners

Dean, Graduate School

March 23, 1990

Date

4-4-90

Wood, William L., Master of Science, 1989 Forestry

Title: An Analysis of Time Components and their Effect on the Efficiency of Several Unequal Probability Sampling Designs.

Director: Alan McQuillan

Stand-specific inventories are required to meet modern planning needs. The costs of such inventories are often too high to sample the entire ownership. The problem is to develop a stand-specific inventory system that yields a known and acceptable statistical error for volume at a minimal cost. This study examined various ways by which total sample time could be reduced namely: using a potentially efficient sampling procedure and finding the optimal ratio of the number of DBHs to height measurements. Also, an estimate of the percentage of the total plot time by measurement (eg. time to take a diameter measurement) was calculated. A field study using five methods of estimating mean cubic feet volume per acre in stands representing three classes; pole, immature sawtimber and old growth in western Montana was conducted. Three different procedures were repeated on a set of plots in each stand. Time measurements were recorded at each visit. The optimal ratio of DBH to height measurements was found to be 3 DBHs to one height for old growth and 4 DBHs to one height for second growth. Five different estimators for cubic foot volume were compared. Using the optimal ratio of DBHs to height with a point sample was found to be best in the second growth stands, while 3P procedures were more efficient in the old growth. The study was extended to include an investigation of estimation versus measurement of height and DBH for their effect on accuracy of cubic volume per acre and trees-per-acre estimation. Finally, the results of this study were used to illustrate a technique for designing a close-to-optimal inventory procedure under differing stand conditions.

TABLE OF CONTENTS

TABLES

ACKNOWLEDGEMENT

I would like to thank my committee and the University of Montana for the opportunity to compete may Master in Forestry. I am grateful for thier patience over years. And finally, I would like to thank Mac Intyre-Stennis for the funding this project.

Section I

CHAPTER 1

INTRODUCTION

Forest inventories are conducted at two distinct levels of resolution. Intensive, stand-specific inventories are conducted for individual stands prior to timber sale preparation or initiation of silvicultural activity. For long-range planning purposes, less intensive techniques are used to inventory the entire forest. Forests are stratified by certain characteristics such as cover type, but at a precision level that usually does not yield reliable estimates for specific stands or small groups of stands.

Modern planning methods, as employed by both public agencies and private timber corporations, require that the entire forest be inventoried at a high level of resolution (Smith 1981). One private company, Champion International, is in the process of changing from a timber-type inventory to a compartment-based inventory system to yield more site-specific data, but field costs represent a significant problem (McQuillan, 1983 personal communication). The Forest Service in Region One has stopped inventorying their commercial forest lands by the stand examination process because of the high cost (Brickell, 1983 personal communication). The Montana State Lands, Division of Forestry, is presently using a "walk-through" sampling procedure to estimate volume and other stand characteristics. A major problem faced by forest managers is to develop a stand specific inventory system that yields a known and acceptable statistical error for volume with a minimal cost.

The cost of conducting an inventory of fixed precision is a function of the following factors: the variation of tree sizes in the population, the spatial distribution of the trees, the efficiency of the sampling methodology, the instruments used in measuring sample trees, accessibility and physical characteristics of the stands, crew skill and, finally, the amount of information needed to meet the inventory objective. An inventory designer has no control over many of these factors such as the variation of tree sizes in a population, the spatial distribution of the trees, the physical characteristics and accessibility of the stand. The remaining factors can be controlled by the designer. Due to the number of factors that are not controllable, no single inventory system can be applied to all stands and still be expected to be cost efficient.

The objective of the inventory influences the choice of sampling design because it dictates what data is to be collected and at what desired level of precision estimates are to be determined. For most forest inventories the minimum output report is an estimate of total volume in board feet or cubic feet by species at a given precision level. The maximal output for most purposes is an estimate of volume in board feet or cubic feet, trees per acre and basal area by species and diameter classes at a given precision level. In practice, most inventories are designed to meet a fixed precision level for total volume and not volume by individual diameter classes or species.

The major cost component of a forest inventory is the field work (Bonner 1972). An important strategy in reducing the total cost of an inventory is to reduce the field costs, while maintaining desired statistical precision. This can be achieved by several methods: reducing the amount of information taken at each plot, using multi--level sampling techniques (Martin and Gerlach 1981), finding the optimum ratio between the number of measurements for a given pair of variables (DBH and height) (Zeide 1984), making estimates of variables instead of physically measuring them, finding the optimal plot size, or by using more efficient sampling methods.

This study compares the effects of using a potentially more efficient sampling method, 3P point sampling, and determining the optimal ratio between heights and diameters as ways of reducing inventory costs. Also, to help inventory planning, a comparison is made of the percent of total time spent for the following basic measures: travel time between measurements, travel time between plots, time spent measuring and estimating diameters at breast height (DBH), time spent measuring and estimating tree heights and time determining the "in" trees on a variable plot.

OBJECTIVES

The objective of this study is to compare the efficiency of five different methods for estimating the mean cubic foot volume per acre in stands representing three classes (pole, immature sawtimber and old growth) in western Montana. All five methods use a variable radius plot to define the sample trees. The first method requires measures of diameters and heights of the selected trees (point sampling, or PS). The second method requires measurements of all tree diameters and a subsample of heights using the optimum ratio (PS_{opt}). This sampling design was simulated using a computer to select a subset of measured heights from the field plot data. The next two methods use Point 3P sampling of the "in" trees. One is based on an estimate of tree height ($3P_{ht}$) and the other based on an estimate of total cubic feet ($3P_{vol}$). The fifth and last method adjusts the sample of 3P heights based on a subsample of actual heights. This method uses the $3P_{ht}$ height estimates and actual tree heights.

The chosen measure of efficiency was the product of total sampling time multiplied by the squared standard error of the mean cubic foot volume (Mesavage and Grosenbaugh 1956). Wages are assumed to remain constant; lower values indicate greater efficiency. Determination of sample size was based on a desired percent standard error for mean cubic foot volume of twenty percent with a 68% confidence level (one standard deviation). Estimates for all standard errors of the mean cubic foot volume per acre, (except for variable plot sampling with all the heights measured), were made using the Bootstrap method (Efron 1982). It has been found that the Bootstrap method can be used to give a reliable estimate for the standard error when the exact formula for the standard error is not known. The exact formula for calculating the standard error for the 3P sample with variable plots is not known except when all the tree heights are measured.

There were four secondary objectives. The first was to obtain an estimate of the optimum ratio between the number of diameters sampled to one height sample for a given stand type. This ratio was used to determine the optimum number of heights to sample for the optimum plot procedure (PS_{opt}). This ratio determination is based on work done by Zeide (1984). An other was to estimate the percent of time spent taking measurements on a variable plot as well as travel time between plots. Also, the measurement times for DBH and heights were compared to times required for estimating them, and the effect of estimation versus measurement on the accuracy of the variables of interest (cubic volume per acre and trees per acre) was investigated. Finally, a method for designing a close-to-optimal inventory technique customized to an individual type of stand was demonstrated.

CHAPTER 2

LITERATURE REVIEW

Forest Sampling Methods

The literature review will be broken into the following sections: a general review of forest sampling methods, how to use 3P sampling and the experiences some people have had with it, how to determine the ratio of measurements, how to use Bootstrap, and a discussion of my selected measure of efficiency.

100% Sampling - An one hundred percent tally yields the most accurate estimates of any of the sampling methods. The error in total volume is only due to the error associated with field measurements and volume equations. Bias can be introduced if volume tables are used that were not developed for that general forest area. The main disadvantages of this system are the high costs of field work and the large amount of data processing involved if a large area is to be inventoried.

Fixed-radius Plot Sampling - Sampling designs using fixed-radius plots require only a small portion of the total population to be measured. The frequency of selecting a tree of a given size on a plot depends on its frequency of occurrence (Wiant 1976). Care must be taken to select the most efficient plot size, because fixed-radius plots can result in sampling too many small trees and not enough large trees for precise and efficient estimates of total volume (Chehock 1982). A small sample size of large trees can yield a higher standard error than the standard error for smaller trees. Fixed-radius plots are most efficient in sampling even-aged stands where all the trees are about the same size (Chehock 1982, Lund 1976 and Wiant 1976).

<u>Variable Radius Plot Sampling</u> - Point or variable radius plot sampling, is highly efficient in volume estimation because sample trees are picked with probability proportional to their basal area. Lahiri (1975) provided one of the earliest descriptions of such a sampling system. Large diameter trees are favored in the sampling process but are weighted less in the data summarization. Variable plot sampling usually yields a more equal distribution of sample trees by DBH classes than fixed plot sampling. Point sampling is most efficient in stands that have a lot of variation in tree size (Chehock 1982, Lund 1976 and Wiant 1976).

<u>3P Sampling Procedure</u> - The 3P sampling method was developed by Grosenbaugh (1964), who later explained and expanded the method (Grosenbaugh 1964, 1965, 1971). Ocular estimates of the characteristic of interest are used together with a measured subsample. The ratio of estimated to measured values in the subsample is used to adjust the ocular estimates of the entire population. The selection of sample trees is proportional to some ocular estimate of a specific characteristic. Thus bigger trees are sampled more frequently than smaller trees. 3P differs from random sampling and systematic sampling in that the variation is based on the ratio between the paired measured and ocular values (Lund 1976). Therefore, with 3P sampling, the expected coefficient of variation is lower and fewer

trees need to be measured for a constant allowable error than with random or systematic sampling.

The earliest application of 3P sampling involved timber sales where all the trees were visited and an ocular estimation of volume was made for each tree. The following steps are performed with 3P sampling:

1) Estimate the number of 3P sample trees desired. This is based on n=(T*CV/E%)^2, where n is number of sample trees, T is t-value with n-1 degrees of freedom, E% is the desired percent sampling error and CV is the best available estimate of the coefficient of variation of the ratio of the measured to estimated tree volumes.

2) Generate a random numbers list with a range restricted to between 1 and the maximum ocular estimate. To do this I wrote a Basic language computer program called RAND. The input requirements are: an estimate of the number of 3P sample trees, the volume of the biggest or tallest tree in the population (K), and the sum of the total predicted volume divided by the number of trees to be sampled (K+Z). This indicates we will select one 3P sample tree for every K+Z accumulation of volume. By increasing Z, the likelihood of drawing a rejection symbol and not actually measuring a sampled tree increases.

3) Visit all the trees in the population. An ocular estimate is made of each tree's volume. This estimate is called KPI. The

KPI value must be greater than 1 but if KPI is greater than K (ie. the tree is bigger than the largest one expected) it becomes a sure-to-be-measured tree and is not included on the normal 3P sampling calculation. These trees are added on at the end of the volume calculation.

4) Next, for trees where 1 <= KPI <= K, the KPI is compared to the first number on the random number list. If the random number is larger than the KPI, the tree is not sampled. But if the random number is equal to or less then the KPI, the tree is sampled. This procedure is continued for all the individuals in the population visited.

On the average, the total number of 3P sample trees is expected to equal the total volume sampled divided by K+Z. Or, equivalently, one 3P sample tree can be expected for each aggregate of KPI totaling K+Z (Grosenbaugh 1964). Charaeristics that are related to volume are measured from sample trees. The "true" volume (YI) is computed in the office. Because of the time saved in estimating volume, the sample trees can be measured more carefully. A Barr and Stroud dendrometer is one of the instruments that can be used to measure the 3P sample trees. This instrument takes heights and diameters at different locations on a tree stem. With the help of a computer program these measurements are converted to a volume estimate (Grosenbaugh 1971). A standard volume table can also be used to estimate the volume of the measured tree. The procedure for doing the office calculations has been well documented (Grosenbaugh 1964, Space 1971, and Wiant 1976).

Field studies have found that 3P sampling with and without the dendrometer performed well in both estimating gross tree volumes and in the practicality of using the system (Bonner 1971, Johnson 1967, Hartman 1967). Volume estimates appeared less biased if the dendrometer was used. Computer simulation also indicated that 3P sampling was an efficient design which gave unbiased estimates and reliable confidence statements (Sharpnack 1965). Schreuder, et. al. (1968,1971) investigated the theory of 3P sampling and conducted some sampling simulation studies; they concluded that a precise 3P volume estimate was biased, although the bias in practice was negligible, that its variance estimator was unreliable, and that other methods may be better than the 3P method. George Furnival found an error in the Schreuder, et. al. (1968,1971) paper (Schreuder 1976). Correction of these errors showed a substantial improvement of the variance estimate (Grosenbaugh 1976).

<u>Point 3P Sampling</u> - Grosenbaugh added multistage options to 3P sampling. This step made it unnecessary to visit every tree in the population. Only a small part of the population was selected, visiting all the trees in fixed or variable radius plots and estimating their volumes. There are several differences when using 3P sampling in conjunction with point sampling. In the first stage, point sampling, one selects trees proportional to basal area, and then

in 3P sampling, one selects individuals proportional to the estimated height of "in" trees. Point-3P sampling therefore selects individuals proportional to basal area (or DBH^2) times height (Grosenbaugh 1971). Since DBH^2*HT is commonly proportional to volume (Van Hooser 1974), this method has theoretical advantages. (Where HT is total tree height and DBH is the diameter at breast height.) Heights of all the first stage trees have to be specified to ascertain whether or not a given tree qualifies as a 3P subsample when KPI is equal or greater than the estimated height (Grosenbaugh 1971). The sample design is based on two coefficients of variation. These are the CV for the sum of DBH^2*HT among locations and the CV for the ratio of actual cubic foot volume of individual trees to DBH^2*ht (Van Hooser 1974).

The estimated CV of the sum of DBH^2*HT among locations is used to estimate the number of plots and the other CV is used to estimate the number of 3P sample "in" trees. It is assumed that the ratio of actual volume to basal area times height is the same for all the trees on the tract (Rennie 1976). If this relationship is questionable then the tract should be stratified into subunits that have similar ratios.

The results of both computer simulation and field study clearly indicate that a two-stage 3P sample estimate for forest wide estimates of the population total volume is quick and accurate (Van Hooser 1974, Wiant 1974, Wiant 1976).

The Balance Between the Number of DBHs and Height Measurements

An important question is: what is the optimal ratio of DBH-to-height measurements on a plot. Measuring all the heights on a plot requires a large proportion of the total plot time. A common practice with forest inventories is to measure all DBHs but not measure all the tree heights on a plot (Forest Service R1, State of Montana and Champion). Sampling rules try to obtain an adequate subsample of heights for either developing height prediction equations or finding a tarif-DBH relationship. These sampling rules vary from one agency to another and yield different sample sizes for heights. The inconsistency of recommendations reflects the lack of a theory for calculating the optimal ratio of measurements of various tree variables. Zeide (1984) in "Balance of Measurements" outlines the theory for finding the ratio that minimizes the standard error of individual tree volumes for a limited total time. This can be applied to finding the optimal mix of measurements for various tree variables. In the present study this will be found for DBH and height so a comparison can be made with the 3P methods using the optimal subsample of heights for a variable plot.

Bootstrap Technique

With the development of computers that are both fast and inexpensive to operate, the use of intensive computations can free statistical theory from two limiting factors that have dominated the field since its beginning: the assumption that the data conform to a bell-shaped curve and the need to focus on statistical measures whose theoretical properties can be analyzed mathematically (Efron et. al. 1983). With the older methods it was generally necessary to make certain unverifiable assumptions about the data before statistical analysis could proceed (Efron et. al. 1983). One assumption was that the data comes from a normal distribution. Experience has shown that the normal distribution has worked well even when the data has only roughly approximated a normal distribution (Efron 1982). This is why statisticians can give reliable predictions even without computers. When this assumption of normality is not met the result is less reliable (Efron 1982). Computer intensive methods can solve most problems of variance estimation without assuming that the data has a normal distribution. The second advantage is that computers can explore such properties numerically even though their exact analysis is currently not feasible (Efron 1982).

The Weak Law of Large Numbers (Reinhardt and Loftsgaarden 1977) guarantees that in large samples, the statistical estimate of a sample-based statistic is very likely to approach the true value of the statistic for the entire population. (A sample of only 15 observations is not considered a large sample). The Bootstrap procedure provides a means of estimating the statistical accuracy of a statistic from the data in a single sample.

With the Bootstrap technique, the process of repeatedly selecting many samples of size n is mimicked in order to find the probability that the values of their estimate fall within various intervals (Efron et. al. 1983). The Bootstrap technique proceeds as follows:

first the n data points are replicated a large number of times, say a billion times. This yields n billion data points. These n billion data points are then mixed together. From these n billion observations many samples of size n are drawn with replacement and the variable of interest is calculated for each sample to produce a set of estimates. The estimate of the standard error for the variable is the standard deviation of the set of estimates.

Measurement of Efficiency

In comparing estimators there must be a measure of efficiency that can be used to determine which one is better, based on some specified criterion. The statistical definition of efficiency is based on the estimated variance. If there are two estimators W_1 and W_2, and both are unbiased estimators for O with variances VAR(W_1) and VAR(W_2), respectively, we will call W_1 more efficient than W_2 if $Var(W_1) < Var(W_2)$ (Larsen and Marx 1981). This definition can be applied only under the condition that both estimators require the same amount of time (or cost) for data collection. The field procedures for the different estimators in this study require different amounts of time. In this study the measure of efficiency is based on the square of the standard error multiplied by the total sampling time for the stand (Mesavage and Grosenbaugh 1965). In this way, variance and cost (approximated by time) are combined into a single composite measure of efficiency.

CHAPTER 3

METHODS

The methods section is divided into two parts: the field procedure and the lab computations.

Field Procedure

1) Eight timber stands, located in Missoula County, were selected through reconnaissance using both maps and aerial photographs to cover the range of conditions typical in the area. Three stand size classes were chosen: mature old growth stands (never logged, 2 stands), pole size stands (having average diameter of 5.0 - 6.0 inches, 1 stand) and immature saw timber stands which were further divided into those in which trees had been cut during the last 50 years (3 stands) and those where no cutting had been done (2 stands). The stands are described in three tables which summarize various statistics. Table 3.1 lists sample-based estimates for CVTS (total stem cubic foot volume per acre based on 16 foot logs), CV4 (Total cubic foot volume, less stump, to a 4 inch top per acre), SV6 bdft/ac (Scribner board feet volume to a 6 inch top per acre based on 16 foot logs), TPA (trees per acre) and BA sqf/ac (square feet of basal per acre). The quadratic mean diameter (Q. DBH) for the stands is found in Table 3.2. The species composition based on CVTS for the study stands is found in Table 3.3. The sampled species in the study were ponderosa pine (*Pinus ponderosa*) (PP), Douglas-fir (*Pseudotsuga mensiesii*) (DF), western larch (*Larix occidentalis*) (WL), logdepole pine (*Pinus contorta*) (LPP), alpine fir (*Abies lasiocarpa*) (AF), and

Engelmann spruce (<u>Pices engelmann</u>) (ES). A narrative description of the stands is located in Appendix A.

Table 3.1

Mean CVTS, CV4, SV6, TPA & BA for 8 Study Stands

Stand ID.	CVTS /acre	CV4 /acre	SV6 bdft/ac	TPA	BA sqf/ac
OLD GR. #1	5477.7	4962.0	21030.6	369.9	196.7
OLD GR. #2	3613.9	2851.2	9962.2	453.8	125.0
POLE #1	3384.7	2244.9	3149.8	720.4	136.0
IM. SW. #1	1809.6	1650.3	5453.5	145.5	72.3
IM. SW. #2	2577.7	2397.6	9026.1	161.5	102.1
IM. SW. #3	1531.4	1390.7	4762.9	150.8	73.6
IM. SW. #4	2645.5	2478.0	10625.7	125.6	100.0
IM. SW. #5	4783.3	4266.1	17054.9	348.6	146.7

Table 3.2

Quadratic Mean Diameter for 8 Study Stands

STAND	Q. DBH inches
OLD GR. #1	9.8
OLD GR. #2	7.1
POLE #1	5.9
IM. SW. #1	9.5
IM. SW. #2	10.8
IM. SW. #3	9.5
IM. SW. #4	12.1
IM. SW. #5	8.8

Table 3.3

Species Composition Based on CVTS for 8 Study Stands

STANDS	PP	DF	WL	LPP	AF	ES
OLD GR. #1	2.1	97.9	-	-	-	-
OLD GR. #2	-	32.6	8.8	44.3	2.9	11.3
POLE #1	-	10.5	6.4	83.1	-	-
IM. SW. #1	38.1	45.1	16.2	0.6	-	-
IM. SW. #2	59.9	27.7	12.4	-	-	-
IM. SW. #3	88.7	9.2	0.8	1.3	-	-
IM. SW. #4	57.6	22.4	11.7	8.2	-	-
IM. SW. #5	15.4	22.0	62.6	-	-	-

2) The stand coefficient of variation (CV) was estimated for the following variables: total cubic foot volume (CV_{vol}) and DBH^2*HT (CV_{ht}), using a reconnaissance cruise. The following is the sampling design for the reconnaissance:

A) Six plots were located in each stand using a single transect.

B) A basal area factor (BAF) was selected prior to sampling to average six to nine trees per plot.

C) The following measurements were taken for the "in" trees by species on the plot: diameter at breast height (DBH) to the nearest tenth of an inch, and height to the nearest foot.

D) The distance from plot center was measured for all borderline trees to determine if they were "in" or "out".

E) The data was processed using the INVTRY (McQuillan et al. 1984) program to calculate the standard deviation (SD) for CVTS.

Then the CV was calculated: $CV=SD/\overline{X}$ where $\overline{X}$ equals the mean cubic foot volume per acre.

3) Next the number of PS plots and 3P sample trees required to meet a total percent sampling error ($E\%_{tot}$) of 20% was calculated for the each of the sampling methods. The number of plots for PS is given by:

$$n=((CV_{vol}*T)/E\%_{tot})^2 \qquad (1)$$

where n is the number of plots, T is Student's t-value with n-1 degrees of freedom at a 68% confidence level (one standard deviation) and CV_{vol} is the estimate for coefficient of variation for CVTS when using point sampling and measuring all the heights (Freese, 1962). The total sample error ($E\%_{tot}$) for the two 3P methods equals the square root of the sum of the square of plot error ($E\%_{plot}$) and 3P sample error ($E\%_{3P}$):

$$E\%_{tot} = (E\%_{plot}^2 + E\%_{3P}^2)^{.5} \qquad (2)$$

This assumes that the variances are independent and the covariance term is neglected (Van Hooser 1974). The best way to distribute the total error between the $E\%_{plot}$ and the $E\%_{3P}$ is to set up a matrix (see Table 3.4).

Table 3.4
Plot Allocation
(plot cv%= 60 and 3p cv%= 30)

Plot % error	5	8	10	12	15
# of plots	144	56	36	25	16
3P % Error	15	12	10	8	5
# of 3P Samples	4	6	9	14	36

Therefore $E\%_{plot} = (E\%_{tot}\hat{\ }2 - E\%_{3P}\hat{\ }2)\hat{\ }.5$. Once this is estimated the following formula is used to find the number of 3P sample trees:

$$n=((CV_{3P}*T)/E\%_{3p})\hat{\ }2 \qquad (3)$$

The $CV\%_{3P}$ associated with the 3P sample is about 30%, since an experienced cruiser can obtain a CV% of about 20% and for a beginner approximately 35% (Metcalf 1983 personal communication). The number of plots can be estimated using formula (3) by substituting E_{plot} and CV_{vol} for $E\%_{3P}$ and CV_{3P}.

4) A random number list for each of the two 3P sampling methods by stand was created using a computer program based on the following input variables:

A) An estimated average of the total number of "in" trees to be sampled on a variable plot .

B) An estimate of the largest "in" tree volume or tallest tree (K) in the stand according to whether one is using point $3P_{vol}$ or $3P_{HT}$ sampling.

C) An estimate of both, the total volume and the total height, from all the plots.

D) An estimate of the total number of trees to be 3P sample trees in the stand.

E) Divide item C by D to obtain (K+Z). A list of random numbers was produced using the computer program RAND.

6) From a theoretical point of view, sample points should be selected randomly. However a random distribution of points over an area is difficult to achieve in practice and most sampling schemes use some form of systematic sampling (Chehock 1982). The most common pattern is a grid having the sampling units in equally spaced rows with a constant distance between units within rows (Freese 1962). The grid is then randomly placed on a map of the stand. This pattern helps insure that the plots are uniformly distributed over the entire stand. Plots for this study were laid out with a systematic grid with a random starting point.

7) The bearing and distance to the first plot were determined from the grid and an aerial photo. A Silva compass was used to determine the bearing and a pacing stick to measure the horizontal distance.

8) Once the plot center was located, a wooden stake was driven into the ground. A flag with the stand identification number, date, distance and bearing to the next plot and sampling method type was tied to the stake.

9) Time was divided into five parts: the time required to determine which trees were "in" trees on the variable plot (T_{baf}), the time required to measure DBHs on all the "in" trees (T_{dbh}), the time required to measure the heights of the "in" trees (T_{ht}), the time required to estimate all the volumes, DBHs or heights of all the "in" trees (T_{est}) and time required to travel from one plot to another plot (T_{travel}). After the plot center was located the next step was to determine the "in" trees. T_{baf} was started when both persons were ready and stopped when all the trees were checked or measured for "in"/"out" status. The recorder flagged all the trees on the variable plot. During the first visit to each plot the DBH was estimated on all "in" trees. The T_{est} for the estimated DBHs was measured and recorded.

10) A separate random number table was used to determine which of the three sampling methods was used for a plot. The other systems were used on subsequent visits to the plot. The field procedures associated with each sampling method were as follows:

A) Point sampling (PS): The DBHs of the "in" trees were measured. T_{dbh} started when the crew member began measuring the first DBH and stopped when all the "in" trees were measured. The DBHs were measured to the nearest tenth of an inch using a diameter tape. The next measurement was height, which was recorded to the nearest foot using a relaskop and a 66' foot tape. T_{ht} began when the crew member started measuring heights on the "in" trees and stopped when all the trees were measured.

B) Point 3P-volume sampling ($3P_{VOL}$): Once the "in" trees were identified, T_{est} for volume estimate was started and continued until an estimate of KPI (volume, CVTS) was made for all "in" trees. The KPIs were compared to a random numbers list to determine if the "in" trees needed to be actually measured for DBH and height (ie. if KPI was equal or greater than the random number). T_{dbh} and T_{ht} were measured for the trees selected on the plot.

C) Point 3P-height sampling ($3P_{HT}$): Once the "in" trees were identified the T_{est} for height was started and continued until an estimate of KPI (height) was made for all "in" trees. Again, if KPI was equal or greater than the random number then the "in" tree DBH and height were measured.

11) Before proceeding to the next plot, the tally sheet was carefully checked over for readability and completeness.

12) T_{travel} was recorded for the time required to travel to the next plot. For future remeasuring, the line was flagged (but flagging time was not included). The procedure was repeated once the new plot center was located for the next plot.

13) When all the plots had been visited once, the procedure was started over again from plot number one. There was a period of at least three days between visits to any one plot to minimize the chance of memory bias. This second time there were only two sampling methods to choose from. On the third occasion the sampling method was which ever one had not yet been used.

14) This entire procedure was repeated for each of the remaining seven stands.

LAB COMPUTATIONS

1) After the field work was completed the data was entered into files on the U of M DEC2065 computer. Data files were built for each stand.

2) The optimal ratio between the frequency of DBH-to-height measurements (Zeide 1983) was calculated first. This ratio was calculated using the following steps:

A) Derive the equation to estimate the ratio of the number of DBHs to be sampled per height measurement to minimize the standard error of volume estimate for the tree (Appendix C);

B) The mean, standard deviation and correlation coefficient was calculated for DBH and height based on the variable plots where all the trees were measured for each stand by species;

C) Average values for T_{ht} and T_{dbh} were calculated by stand based on a weighted average for the field study;

D) Due to the complex nature of the final equation in part A) a computer program was written to calculate the optimum ratio of number of DBH-to-height measurements by stand and species;

E) Finally a stand ratio of DBH-to-height measurements was calculated based on a weighted average CVTS by species.

3) The next set of calculations involved time data. For each stand and sampling procedure the following were calculated:

A) The average time by stand for T_{baf}, T_{dbh}, T_{ht}, T_{est} (volume DBH, and height) and T_{travel}.

B) The percentage of the total time by T_{dbh}, T_{ht}, T_{travel}, and T_{baf} were calculated. Also a percentage time breakdown was calculated for T_{est} (DBHs and heights).

C) The formula to calculate the total time for each method was as follows: for the $3P_{vol}$ and $3P_{ht}$ methods, $T_{total} = T_{baf} + T_{dbh} + T_{ht} + T_{est}$ (T_{dbh} and T_{ht} were based on the 3P sample of the "in" trees), for the Ind. $3P_{ht}$ method, $T_{total} = T_{baf} + T_{dbh} + T_{est}$ (T_{dbh} was based on the PS sample of DBHs and T_{est} was based on the plot $3P_{ht}$ sample of heights), for the PS_{opt} procedure was, $T_{total} = T_{baf} + T_{dbh} + T_{ht}$ (where T_{dbh} was based on the PS sample of DBHs and T_{ht} was estimated based on the optimal ratio for the stand times the number of trees on the plot, times the average time to measure a height on the plot) and last for the PS, method $T_{total} = T_{baf} + T_{dbh} + T_{ht}$ (where T_{dbh} and T_{ht} were based on all the trees measured).

4) The INVTRY program was modified so that 3P estimates could be calculated. Also the Bootstrap method was incorporated for calculating the standard error. The Bootstrap procedure causes a large number of repeat samples of size n to be taken with replacement out of the original sample of size n. To do this, the original sample was replicated 200 times. For each of these samples of size n the sample statistics are calculated. The Bootstrap estimate for the Standard Error of the estimator is equal to the Standard Deviation of these sample statistics.

5) The following estimators were computed based on point sampling;

A. PS all the DBHs and heights measured.

B. PS_{opt} a subsample of heights that were measured based on the optimal ratio and all the DBHs measured.

C. IND. $3P_{HT}$ used a 3P subsample of heights to estimate a ratio of the measured heights to estimated heights on each plot to calibrate the estimated heights and all the DBHs measured.

D. $3P_{HT}$ used 3P sampling with KPI equal to the estimated height of the tree.

E. $3P_{cv}$ used 3P sampling with KPI equal to the estimated volume of the tree.

The formula for calculating CVTS for the 3P sampling methods is:

$$CVTS = \frac{BAF * H_o}{K * M} \sum_{i=1}^{K} Y_i \,/ (B_i * H_{oi})$$

where BAF is the basal area factor,

H_o is the sum of all the KPIs on all the plots

M is the number of 3P sample trees

K is the number of plots

Y_i, B_i, and H_{oi} are the actual volume, basal area and the KPI of the ith 3P sample tree.

CHAPTER 4

RESULTS AND DISCUSSION

Sampling Time Components

In this study measurement time was divided into four parts. Time is a proxy for cost, but there is no attempt to convert time into dollars.

1) Travel Time (T_{travel}) -- Travel time (T_{travel}) is the time required to travel from plot to plot or from the starting point to the first plot. The three main influences on T_{travel} are the distance between plots, how accurately the plots are to be located, and the physical characteristics of the stand. The greater the distance between plots, the longer it is going to take to travel between plots. The distance between plots is a function of the desired precision, acreage of the stand and plot layout. If plot location must be know more accurately, more sophisticated instruments are required. These instruments slow down the speed at which one can move through the woods. A Silva compass and a pacing pole were used to navigate between plots for this study. The average travel time is affected by the fuel loading, brush, density of the stand and the slope. The fuel loading and brush make it hard to walk around. The density of brush and trees affects how far one can see without taking another compass reading, and dense stands are also harder to move through.

In this study an entire stand could be sampled in one day or less, so that retracing steps to resume work was unnecessary. The average

Travel time is shown in Table 4.1 as well as other average time components to be referred to later.

Table 4.1

Average Time per Measurement and BAF by Stand

STANDS	AVERAGE TIME (min.) T_{baf}	T_{dbh}	T_{ht}	T_{travel}	BAF[1]	TPP[2]
OLD GR.#1	.59	.35	1.08	2.07	20	7.0
OLD GR.#2	.73	.42	1.35	3.14	20	6.25
POLE #1	.63	.21	.92	1.81	20	7.0
IM.SW. #1	.45	.29	.94	2.14	10	7.23
IM.SW. #2	.51	.26	.76	1.67	10	10.21
IM. SW. #3	.40	.23	.64	1.94	10	7.35
IM. SW. #4	.59	.33	.82	1.79	20	5.0
IM. SW. #5	.57	.37	1.03	2.48	20	7.33
ALL STANDS	.56	.31	.94	2.13	-	-

[1] BAF is the basal area factor (sq²/acre).
[2] TPP is the average trees per plot.

Stand OLD GR. #2 had the highest average time between plots (Table 4.1). This stand had heavy fuel loads, dense brush and a moderately steep slope. The stands with the lowest average T_{travel} were the flattest and had the least amount of fuels. T_{travel} as a percent of total plot time, when all the tree heights are measured, ranked third in magnitude (Table 4.2). Because travel time is so likely to vary in different stands, I next simulated an increase in distance between plots to cover a variety of situations.

Doubling the travel time for the study stands translates into an increase in the distance between plots from 3 to 6 chains. This causes T_{travel} to become second only to height time on a percentage basis in all but stands IM. SW. #2, pole #1 and OLD GR. #1 (Table 4.3). When the travel time is four times the original value, travel time has the highest percent except for height OLD GR. #1, where height is still ranked number one (Table 4.4). Measuring only a subsample of heights on the plot causes the percent of travel time to increase to a higher percent of total plot time.

Table 4.2

Percentage of Total Time Required to Perform Four Functions for PS Sampling of Eight Sample Stands

STAND	T_{travel}	T_{baf}	T_{dbh}	T_{ht}
OLD GR.#1	10.18	28.58	13.70	47.53
OLD GR.#2	17.89	25.89	13.26	42.97
POLE #1	13.22	32.15	10.57	43.91
IM. SW. #1	14.71	28.11	13.62	43.56
IM. SW. #2	10.21	31.90	15.63	43.27
IM. SW. #3	14.49	28.29	13.80	39.43
IM. SW. #4	18.23	30.01	15.12	36.65
IM. SW. #5	15.93	26.96	14.35	42.78
ALL STANDS	14.36	28.73	13.64	42.89

Table 4.3

Percentage of Total Time Required to Perform Four Functions for PS Sampling of Eight Sample Stands (Two Times the Average T_{travel} Time.)

STAND	T_{travel}	T_{baf}	T_{dbh}	T_{ht}
OLD GR. #1	18.48	25.94	12.44	43.13
OLD GR. #2	30.34	21.96	11.25	36.45
POLE #1	23.35	28.40	9.47	38.78
IM. SW. #1	25.64	24.54	11.87	37.98
IM. SW. #2	18.53	28.99	13.27	39.27
IM. SW. #3	31.21	23.87	11.96	33.28
IM. SW. #4	30.84	25.38	12.79	30.99
IM. SW. #5	27.49	23.24	12.38	36.90
ALL STANDS	25.73	25.29	11.88	37.10

Table 4.4

Percentage of Total Time Required to Perform Four Functions for PS Sampling of Eight Sample Stands (Four time the Average T_{travel} Time.)

STAND	T_{travel}	T_{baf}	T_{dbh}	T_{ht}
OLD GR. #1	31.19	21.90	10.50	36.41
OLD GR. #2	46.56	16.85	8.63	27.96
POLE #1	37.86	23.02	7.57	31.44
IM. SW. #1	40.82	19.51	9.45	30.23
IM. SW. #2	31.27	24.42	11.20	33.13
IM. SW. #3	47.57	18.19	8.87	25.36
IM. SW. #4	47.14	19.40	9.77	23.69
IM. SW. #5	43.12	18.23	9.71	28.95
ALL STANDS	40.70	20.19	9.46	29.65

2) Variable Radius Plot Determination Time (T_{baf}) -- The next part of measurement time is that required to determine the "in" trees on a variable plot (T_{baf}). The main factors that affect T_{baf} are: the number of measured trees on the plot, the density of the stand, size of the trees, brush and slope. The density of the stand affects the ease of viewing the trees through the Relaskop. More care must be taken in difficult conditions so trees will not be missed. Big trees often present problems because of the greater distance from the plot center that they can be while still being in the plot. Also, if a big tree is borderline then the measurement of limiting distance will likely take longer due to the increased distance from the plot center. Brush increases T_{baf} because it takes longer to see the "in" trees on the plot and measure borderline trees.

Also, slope increases the time necessary to move between the trees and the plot center. T_{baf} has the second highest percent of total time after height (T_{ht}) (Table 4.2). Stand Pole #1 had the highest percent time. This can be partly explained by the high density of small trees in the stand and the low average time for DBHs and heights. Stand Old GR. #2 had the highest average T_{baf} per tree (Table 4.2). The reasons for this are the high fuel loading, steep slope and dense brush. Stand Pole #1 ranked second.

3) Diameter Measurement Time (T_{dbh}) -- The next time measurement, T_{dbh}, is the time required to measure the diameter at breast height for the sample trees on the plot. The main factors that affect T_{dbh} are size of the trees, (bigger trees take longer because of the time needed to reach around the tree), the amount of fuels, brush and slope steepness; these factors reduce the speed at which one can move from tree to tree, thus increasing T_{dbh}.

Stand OLD GR. #2 had the highest average time per tree (Table 4.1) and the second lowest percent of total time (Table 4.2). This was due to the fuel, brush and slope steepness. Stand Pole #1 had the lowest average time per tree and the lowest percent of total time (Table 4.2). This was due to the density of the stand (it was a short walk to the next tree) and the small size of the trees. On a percent basis of total time, T_{dbh} and T_{travel} had similar values. As the T_{travel} time was increased (2X and 4X) the effect on the percent of T_{dbh} was small. Generally DBH is an important measurement due to its effect on the estimate of TPA, BA and tree volume equations, because DBH is usually raised to a power close to 2. One practical way to reduce T_{dbh} is to visually estimate DBHs. The difference between the time to estimate DBH and measure DBH as a percent of the measurement time ranges between 53.6 and 74.8% (Table 4.5). Dividing this difference by the total plot time (T_{tot}) when all heights are measured, the percentages range between 6.45 and 11.31% (Table 4.5). On the average, total time can be reduced by about 9% when all the tree heights are measured and DBHs are estimated. If the difference is divided by the optimal plot time (T_{opt}) with a subsample of heights, the percentages range from 10.12 to 15.78% (Table 4.5).

Table 4.5

Characteristics of Diameter Measurement Time by Stand

STAND	Measurement Time, T_{dbh} DBH Estimated E[1]	DBH Measured M[2]	Difference M-E	Percent Difference %D[3]/M	%D/T_{tot}	%D/T_{opt}
OLD GR. #1	4.83	16.73	11.93	71.31	9.77	14.86
OLD GR. #2	5.63	18.65	13.02	69.80	9.26	12.80
POLE #1	5.65	14.48	8.83	60.98	6.45	10.15
IM. SW. #1	17.03	43.60	25.97	59.55	8.11	11.59
IM. SW. #2	12.18	33.48	21.30	63.61	9.31	13.48
IM. SW. #3	9.40	20.28	10.88	53.65	7.40	10.12
IM. SW. #4	3.37	13.37	10.00	74.82	11.31	15.78
IM. SW. #5	11.83	26.77	14.94	55.80	8.00	11.74
ALL STANDS	8.74	23.42	14.61	63.69	8.70	12.57

[1] E = time to estimate variable
[2] M = time to measure variable
[3] D = difference (M-E)

<u>4) Height Measurement Time (T_{ht})</u>

A) 100% height measurement -- The time needed to measure the "in" trees for height (T_{ht}) was the last time measurement. If all the heights are measured on the plot this consumes the greater percentage of total time of all the variables, about 43% of the total time on the average (Table 4.2).

Height measurements are affected by slope and ease of getting a complete view of the tree(s), stand density, and fuel loading. Another important factor is the number of trips out from plot center one has to make to be able to see all the tree tops. This is affected by the slope, density, spatial distribution, number of sample trees, brush and whether there is a one-person or two-person crew. (I had a 2-person crew.)

The stand that had the most brush and fuel loading had the highest average time per height, OLD GR. # 2 (Table 4.1). On a percent of total time basis OLD GR. #1 had the highest (Table 4.2). This was probably caused by the steep slope, tall trees and the high number of average trees per plot. The two stands with the lowest percent had a low density in terms of basal area and trees per acre, gentle slope, little brush and low number of trees per plot.

One way to reduce T_{ht} is to estimate heights. If the time for estimating all heights is compared to the time required to measure all the heights, the reduction in time (as a percent of measured) is about 74% for all stands (Table 4.6). This difference expressed as a percent of total time is about 31 % (Table 4.6).

Table 4.6

Characteristics of Height Measurement Time by Stand

STAND	Measurement Time, T_{ht} Height Estimated E	Height Measured M	Difference M-E	Percent Difference %D/M	%D/T_{tot}
OLD GR. #1	12.03	58.03	46.0	79.27	37.67
OLD GR. #2	12.17	60.42	48.25	79.86	34.31
POLE #1	17.20	60.13	42.93	71.40	31.35
IM. SW. #1	40.08	139.45	98.65	70.74	30.82
IM. SW. #2	29.85	99.05	69.20	69.86	30.24
IM. SW. #3	16.68	57.97	41.29	71.23	28.08
IM. SW. #4	8.08	32.40	24.32	75.06	27.51
IM. SW. #5	20.70	79.80	59.10	74.06	31.68
ALL STANDS	19.60	73.41	53.72	73.94	31.46

B) Optimal Ratio Height Measurement Time -- The optimal ratio has an interesting effect on the percent of total time by measurement. Now T_{baf} is the highest (Table 4.7). For most stands the percent of T_{ht} and T_{dbh} are very close to the same value under optimal conditions. In the Pole #1, IM. SW. #4 and IM. SW. #5 stands the percent of total time taken by T_{dbh} is considerably greater than that taken by T_{ht}. As Table 4.7 shows, most stands, T_{travel} (actual) is the second highest value, after T_{baf}.

Table 4.7

Percentage of Total Time Required to Perform Four Functions for Optimal PS Sampling of Eight Sample Stands

STAND	T_{travel}	T_{baf}	T_{dbh}	T_{ht}
OLD GR. #1	15.48	43.48	20.84	20.21
OLD GR. #2	24.72	35.78	18.33	21.16
POLE #1	20.81	50.63	16.88	11.67
IM. SW. #1	21.01	40.16	19.46	19.38
IM. SW. #2	14.38	44.93	20.61	20.08
IM. SW. #3	25.28	38.67	18.86	17.20
IM. SW. #4	25.43	41.85	21.09	11.63
IM. SW. #5	23.35	39.48	21.03	16.14
ALL STANDS	21.31	41.87	19.64	17.18

Table 4.8

Characteristics of Height Measurement Time Based on Optimal DBH-to-Height Ratio by Stand

STAND	Measurement Time, T_{ht} Height Estimated E	Height Measured M	Difference M-E	Percent Difference %D/M	%D/T_{vol}
OLD GR. #1	12.03	16.23	4.20	25.88	5.23
OLD GR. #2	12.17	21.52	9.35	43.48	9.19
POLE #1	17.20	10.15	-7.05	-69.46	-8.17
IM. SW. #1	40.08	43.42	2.62	6.03	1.12
IM. SW. #2	29.85	32.63	2.78	8.52	1.71
IM. Sw. #3	16.68	18.49	1.81	9.79	1.68
IM. SW. #4	8.08	7.37	-0.71	-9.60	-1.11
IM. SW. #5	20.70	20.54	-0.16	-0.78	-0.13
ALL STANDS	19.60	21.29	1.61	1.73	1.19

There is no significant time advantage in estimating the height compared to using the optimal ratio of DBH-to-height measurements for the stands, except for the old growth stands (Table 4.8).

Ratio of Measurements

The equation for determining the optimal DBH-to-height ratio is derived in Appendix C. The objective is to minimize the standard error of the mean volume of one tree. The squared standard error approximated by a taylor series expansion. The equation for estimating total time (T_{tot}) spent on height and diameter measurements is solved for the number of height measurements (n_{ht}). n_{ht} is substituted into the squared standard error equation to yield the following equation:

$$
\begin{aligned}
&[SE(V)]^{2}=(\partial V/\partial DBH)^{2}*Var(DBH)/n_{dbh}+(\partial V/\partial HT)^{2}*\\
&Var(H)*T_{ht}/(T_{tot}-n_{dbh}*T_{dbh})+2*B*C*(\partial V/\partial DBH)*(\partial V/\partial HT)*\\
&r(DBH,HT)*(SD(DBH)/n_{dbh}^{.5})*SD(HT)*[T_{ht}/(T_{tot}-T_{dbh}*n_{dbh})]^{.5} \qquad (1)
\end{aligned}
$$

where DBH and HT are the arithmetic mean height and diameter respectively, SD is their respective standard deviation, Var is their respective variance, r(DBH,HT)is the correlation coefficient, T_{dbh} is the average time to measure the diameter of a tree and n_{dbh} is the number of diameter measurements. Equation 2 is the first derivative of the first equation.

$$
\begin{aligned}
&dV/dn_{dbh}=(-1)*(\partial V/\partial DBH)^{2}*Var(DBH)/n_{dbh}^{2} + (\partial V/\partial HT)^{2}*\\
&\quad Var(H)*T_{ht}*T_{dbh}/(T_{tot}-n_{dbh}*T_{dbh})^{2} +\\
&\quad 2*B*C*(\partial V/\partial DBH)*(\partial V/\partial HT)*r(DBH,HT)\\
&*[-.5*(SD(DBH)*SD(HT)*T_{ht}^{.5}/n_{dbh}^{1.5})*(T_{tot}-T_{dbh}*n_{dbh})^{-.5} +\\
&.5*SD(HT)*SD(DBH)*T_{ht}^{.5}*T_{dbh}/n_{dbh}^{.5}*(T-T_{dbh}*n_{dbh})^{-1.5}] \qquad (2)
\end{aligned}
$$

The number of DBH samples is estimated by setting equation 2 equal to zero. Due to the complex nature of equation 2, it was solved by writing a computer program. The first part of the program is an interactive part for entering data such as; average T_{ht} and T_{dbh} (Table 4.1), species (Table 4.9), total time (constant) and the last four variables by stand and species namely, average DBH and HT (Table 4.9) and standard deviation for HT and DBH (Table 4.9). The main body of the program uses an iterative process to find the number of DBH measurements required to minimize the variance of individual tree volumes. The stand DBH-to-height measurement ratio (Table 4.10) was calculated by weighting the stand's species DBH-to-height measurement ratios (Table 4.10) by CVTS.

Table 4.9

Stand Statistics By Species within Each of 8 Stands

STAND	$\overline{DBH}$	σ_{dbh}	$\overline{HT}$	σ_{ht}	r(DBH,HT)	% CVTS	SP
OLD GR.#1	10.5	3.4	58.6	14.5	.96	100.0	DF
OLD GR.#2	10.8	7.3	56.0	36.1	.98	36.5	DF
OLD GR.#2	5.5	3.1	46.1	25.2	.96	48.2	WL
OLD GR.#2	4.5	2.9	27.6	17.6	.98	15.2	LP
POLE #1	6.2	1.6	51.0	5.9	.83	100.0	LP
IM. SW.#1	9.8	5.0	52.9	25.0	.97	45.8	PP
IM. SW.#1	7.4	4.3	42.2	24.2	.98	54.8	DF
IM. SW.#2	10.7	3.7	60.6	19.6	.95	68.3	PP
IM. SW.#2	8.8	3.0	51.7	16.5	.94	31.7	DF
IM. SW.#3	10.9	3.3	52.2	13.0	.93	100.0	PP
IM. SW.#4	8.6	7.4	41.1	33.2	.98	67.8	PP
IM. SW.#4	13.7	3.8	68.7	70.8	.75	32.2	DF
IM. SW.#5	8.8	5.5	69.5	27.2	.88	100.0	WL

TABLE 4.10

Stand Characteristics and Ratio of Measurement Time for Stand by Species

STAND	DBH CV%	HT CV%	Average T_{ht} mins	Average T_{dbh} mins	RM[1]	T_{ht}/T_{dbh}	STAND RM	SP
OLD GR.#1	32.5	24.7	1.08	.35	3.3	3.1	3.3	DF
OLD GR.#2	68.1	64.6	1.35	.42	3.3	3.2	3.1	DF
OLD GR #2	57.1	54.6	1.35	.42	3.1	3.2		WL
OLD GR #2	66.4	63.7	1.35	.42	2.7	3.2		LP
POLE #1	25.5	11.5	.92	.21	7.1	4.4	7.1	LP
IM. SW.#1	50.7	47.2	.94	.29	3.9	3.3	3.8	PP
IM. SW.#1	58.0	57.3	.94	.29	3.8	3.3		DF
IM. SW.#2	34.3	32.4	.76	.26	3.6	2.9	3.4	PP
IM. SW.#2	33.7	31.9	.76	.26	3.1	2.9		DF
IM. SW.#3	30.0	25.0	.64	.23	3.8	2.8	3.8	PP
IM. SW.#4	86.6	80.9	.82	.33	4.8	2.5	4.2	PP
IM. SW.#4	27.7	103.1	.82	.33	2.8	2.5		DF
IM. SW.#5	61.6	39.1	1.03	.37	4.6	2.7	4.6	WL

[1] RM = ratio DBH-to-Height measurements

Zeide (1984) recommends in general that the same amount of time be spent on both height measurements and DBH measurements. If this is true, then the ratio of T_{ht}-to-T_{dbh} would equal the stand ratio of DBH-height measurements. The results for the two old growth stands and IM. SW. #1 (Table 4.10) approximately concur with this recommendation. In the other stands (Table 4.10) more time should be spent on measuring DBHs than heights.

Comparison of Five Different CVTS Estimators

This section presents the results in terms of the efficiency of the different estimators. The measure of efficiency is the total sample time multiplied by the squared standard error of the mean cubic foot volume (Mesavage and Grosenbaugh 1965). Low numbers are more efficient because less time will be spent to achieve a given precision level.

Table 4.11

The Efficiency of the Sampling Methods

Stand	PLOT $3P_{CV}$	PLOT $3P_{HT}$	IND $3P_{HT}$	PS Optimal	PS Total
OLD GR. #1	457	254*	444	337	557
OLD GR. #2	289	173	159*	190	297
POLE #1	129	145	169	103*	193
IM. SW. #1	94	80	94	75*	128
IM. SW. #2	77	49*	95	52	84
IM. SW. #3	57*	72	89	59	85
IM. SW. #4	71	34	32	29*	39
IM. SW. #5	328	240	482	201*	321
ALL STANDS	188	131	192	131	213

* = Most efficient for that stand

The optimal plot procedure is clearly the best in stands Pole #1, IM. SW. #1, IM. SW. #4 and IM. SW. #5 (Table 4.11). Plot 3P-HT is most efficient in stands OLD GR. #1 and IM. SW. #2 (Table 4.11). Plot 3P-CV is the most efficient in the Stand IM. SW. #3. IND. 3P-HT was the most efficient for stand OLD GR. #2 (Table 4.11). However, the optimal plot procedure was either the best or a close alternative in all cases.

CHAPTER 5

CONCLUSIONS

Estimating DBH and/or HT reduced the total time spent on a plot. T_{travel} is an important part of the total cruise time and cannot be reduced in most cases. Once T_{travel} becomes large, then there is no point to developing methods that reduce the time spent on measurements. One method to reduce T_{baf} is to not measure borderline trees and count every other borderline tree as "in". The more experienced the crews, the more reliable the estimates of "in" trees will be. Over the long run it might average out. One problem is that everyone sees borderline trees differently. One tree may appear borderline to one person and not to another. Over the long run the bias may be minimal for any one person if he or she measures an occasional borderline tree as a self-check, but the bias from combining plots from different crews is unknown.

Estimation of DBHs reduced the total cruise time by about 9% when all the heights were measured or by about 12.5% when the optimal ratio of heights is used. Estimating heights probably requires more than one trip out from the plot center in order to see all the tree tops. The optimal ratio requires measuring only two or three heights per plot (assuming a DBH-to-height ratio of 3.0, and 6-8 "in" trees per plot). Measuring these heights would require at the maximum two or three trips out from the plot center which should be less than the number of trips required to estimate all the heights. This is important since the time consuming part of taking heights is walking out the appropriate horizontal distance from the base of the tree.

It is important to consider the following factors when attempting to reduce the total measurement time:

1) the effects of subsampling a variable on the error estimate,
2) the effects of subsampling on the percentage break down of total time,
3) the instrument(s) used to measure the variable,
4) whether estimation of the variable is possible (the probability of meeting the desired accuracy standard) and
5) the importance of the variable to the estimation of the statistic of interest (sensitivity).

The optimal DBH-to-height measurement ratio should be 3-to-1 for old growth stands and between 4-to-1 and 6-to-1 for second growth stands. The lower the CV% for heights in a stand, the higher the ratio should be.

The optimal plot method (method using the DBH-to-height measurement ratio) appears to perform better in the second growth stands. The optimal plot method was very close to the most efficient method in IM. SW. #2 and IM. SW. #3. The optimal plot method is not the best procedure for the two old growth stands. This is partly due to the higher variability in volume usually found in old stands. However, If the added time required to prepare the random numbers list and sample size allocation for 3P were taken into consideration, the optimal plot method would probably be the most efficient method overall.

Section II

The purpose of this section is to extend the study presented in Section I in two directions. In chapter 6 I investigate the effects of estimating rather than actually measuring both DBHs and heights on cruise accuracy. In chapter 8 I use time and motion study techniques to show how inventory cost can be minimized by the determination of the optimal combination of basal area factor (BAF) and the number of sample plots(n).

Finally, in Section III (chapter 9), I use the results from Sections I and II to draw conclusions and make general recommendations about how inventories can be designed for greater efficiency.

CHAPTER 6

ESTIMATION of TREE VARIABLES

In this chapter, I examine the effect of estimating tree characteristics (DBH and HT) instead of measuring them as a method for reducing the total time for inventorying stands. A primary question is: what, if any, significant effect does estimation have on the accuracy of summary statistics? In this chapter I examine the effects of estimating diameters (DBHs to the nearest tenth of an inch) and estimating heights (to the nearest foot), on estimates for trees per acre (TPA) and for total cubic feet volume per acre (CVTS).

Hypothesis and Methods

Only four of the seven possible comparisons were made.

1) The first comparison is between total trees per acre (TPA) derived from an ocular estimate of DBHs, and TPA derived from measured DBHs. The hypothesis to be tested is H_0: $TPA_e = TPA_m$ versus H_1: $TPA_e \neq TPA_m$.

2) The second comparison is between total cubic foot volume (per acre) using estimated DBHs and that derived from measured DBHs. In this comparison tree heights are measured in both cases. The hypothesis to be tested is H_0: $CVTS_{ed} = CVST_{md}$ versus H_1: $CVTS_{ed} \neq CVTS_{md}$.

3) The third comparison is between total cubic foot volume (per acre) based on estimated heights and that based on measured heights. This comparison uses measured DBHs in both cases. The

hypothesis tested is H_0: $CVTS_{eh} = CVST_{mh}$ versus H_1: $CVTS_{eh} \neq CVTS_{mh}$.

4) The fourth and last comparison is between total cubic foot volume per acre based on measured DBHs with heights, and that based on estimated DBHs with estimated heights. The hypothesis to be tested is H_0: $CVTS_{ehd} = CVST_{mhd}$ versus H_1: $CVTS_{ehd} \neq CVTS_{mhd}$.

The field data were collected from the same eight stands used in Section I. Each stand was visited twice. The first time, an ocular estimate of the DBH was made on all the "in" trees on each plot. The next step was either to ocularly estimate all the trees for height or, to measure all the tree DBHs and heights. The same person did the estimation for the entire stand to minimize human variation. The four sets of data, (measured diameters and heights, estimated diameters and measured heights, measured diameters and estimated heights, and estimated diameters and heights), were then compiled and processed through the INVTRY program (McQuillan et al. 1984) to calculate TPA and CVTS by plot for all the stands. With this information, four paired T-tests were performed. The level of significance chosen for the paired T-test was 5% (alpha = .05). The results of these tests are shown in Tables 6.1 through 6.4.

Results

Table 6.1
Paired t-Test Between Measured and Estimated DBHs
for Total Trees per Acre

SAMPLE	1 TPA_{md}	2 TPA_{ed}	1 - 2	T-VALUE
OLD GR.#1	369.85	349.23	20.6	.095
OLD GR.#2	453.82	420.83	33.0	.339
POLE #1	720.38	730.09	-9.7	.087
IM.SW.#1	145.51	134.97	10.5	.429
IM. SW.#2	161.46	152.89	8.6	.481
IM. SW.#3	150.78	155.21	-4.4	-.118
IM. SW.#4	125.59	122.17	3.4	.066
IM. SW.#5	348.56	319.72	32.3	.303

Table 6.2

Paired t-Test Between Measured and Estimated DBHs
for Total Cubic Feet per Acre

STANDS	1 $CVTS_{em}$	2 $CVTS_{ed}$	1 - 2	T-VALUE
OLD GR.#1	5477.67	5488.75	11.08	.012
OLD GR.#2	3613.93	3619.92	5.99	.009
POLE #1	3384.67	3483.71	99.04	.194
IM. SW.#1	1809.62	1803.58	-6.04	.021
IM. SW.#2	2577.69	2573.02	-4.67	.017
Im. Sw.#3	1531.35	1531.40	.05	.0001
Im. Sw.#4	2645.54	2656.21	-10.67	.036
IM. SW.#5	4783.34	4790.07	6.73	.012

Table 6.3

Paired t-Test Between Measured and Estimated Heights for Total Cubic Feet per Acre

STANDS	1 $CVTS_{mh}$	2 $CVTS_{eh}$	1 - 2	T-VALUE
OLD GR.#1	5477.67	5496.40	18.73	.019
OLD GR.#2	3613.93	3279.88	-334.05	.559
POLE #1	3384.67	3535.32	150.65	.296
IM. SW.#1	1809.62	1672.18	-137.44	.508
IM. SW.#2	2577.69	2476.76	-100.93	.422
IM. Sw.#3	1531.35	1733.67	202.32	.563
IM. Sw.#4	2645.54	2624.29	-21.25	.074
IM. SW.#5	4783.34	4671.49	-111.85	.184

Table 6.4

Paired t-Test Between Measured Heights and DBHs with Estimated Heights and DBHs for Total Cubic Feet per Acre

STANDS	1 $CVTS_{mhd}$	2 $CVTS_{ehd}$	1 - 2	T-VALUE
OLD GR.#1	5477.67	5507.51	29.84	.031
OLD GR.#2	3613.93	3483.83	-130.15	.216
POLE #1	3384.67	3524.14	139.47	.274
IM. SW.#1	1809.62	1784.68	- 24.94	.089
IM. SW.#2	2577.69	2663.78	86.09	.347
IM. SW.#3	1531.35	1730.93	199.58	.555
IM. SW.#4	2645.54	2636.29	- 9.25	.032
IM. SW.#5	4783.34	4677.94	-105.40	.176

There was no significant difference between the two procedures compared in the previous four tables for any of the stands at the chosen alpha level.

That is, there was no statistical difference between the estimators utilizing estimated DBHs and/or HTs as compared to those using actual measured DBHs and/or HTs. From this I conclude the following: (1) estimating DBHs does not significantly affect the mean total number of trees per acre or the estimate of total cubic foot volume per acre when heights are measured. (2) With measured diameters for these eight stands, total cubic foot volume per acre estimates are not affected by estimating heights. And finally (3), that estimating both heights and DBHs is not statistically different from measuring both of them.

Discussion

In comparing the differences for $CVTS_{ed}$ (table 6.2) versus $CVTS_{eh}$ (table 6.3), it is not surprising that this difference is greater when heights are estimated. It is harder to get an accurate estimate for heights than DBHs for the following reasons: the distance (in feet) from the observer to the point of estimation is much larger for heights, it is harder to check oneself when measuring heights, the angle in terms of slope and lean of the tree has to be taken into account, and seeing the top of tree may be difficult in dense stands or on steep slopes.

There are some ways to make estimation more accurate. The first is practice. Visual estimation is best if it is done every day so personnel can develop their skills, although in this study an every day practice session did not occur. One good rule is to start out each day measuring the first sample trees so the observer can check himself. It is also important to move around the plot while estimating to get a good view of all the trees. Also, ocular estimates of DBHs should be checked with a diameter tape periodically.

Another factor is the experience of the crew. The crews doing the field work for this study did not have much experience with ocular estimation although they had experience doing forest inventory work. They practiced a couple of days before starting. More experienced crews should produce better results if their habits do not become sloppy. It may be more cost effective in the long run to retain more experienced crews. With contract work, a lower accuracy standard for DBH measurements (such as the nearest one inch class) or for heights (such as to the nearest five or ten feet) may be stipulated without impairing results. Thus the contractor could either estimate the DBHs or measure them depending on his own experience and skill. This should reduce sampling costs because contractors would likely start estimating in order to be more competitive.

The intended use of the information should be the driving force behind the decision whether or not to estimate tree parameters. Generally, most kinds of decision-support analyses are more sensitive to the standard error associated with total volume than to small changes in the diameter class estimates for CVTS or TPA. People in earlier time used more estimation of tree characterics or volume, but today variables tend to be measured to strict accuracy standards. One reason is that the decision-support system (frequently computer models of various kinds) appears to require more accurate data. However, this may be a false assumption. More research is needed to determine the sensitivity of the decision-support system to changes in measurement procedures so that economically efficient accuracy standards can be developed. The time saved could, it seems, be better utilized to establish more plots so that the standard error of the variable of interest (TPA or CVTS) could be reduced. Alternatively, the target standard error could be achieved at lower inventory costs.

CHAPTER 7

OPTIMIZATION of PLOT SIZE and NUMBER - A CASE STUDY

In designing stand inventories two critical decision variables are: the number of plots needed and the size of each plot. I am assuming that the stand characteristic (CVTS or TPA) of interest has already been identified.

There are two rules-of-thumb in common usage for estimating the number of plots needed for forest inventory. The first rule is one plot per ten acres with a minimum of three plots per stand, and the second is based on percent of total acres to be sampled: a 10% cruise of a 20 acre-stand would require that two acres be sampled. I used the first method while working for the Forest Service; the second method is used by the Montana Department of State Lands, Operations Division.

In determining the plot size for the first rule-of-thumb, the individual picks a plot size (by selection of BAF) such that an estimated average of four "in" trees per variable-radius plot will be selected. In the second rule, a fixed plot was used. So, if a tenth-acre fixed-area plot size was chosen for example, 20 plots would be needed to sample 2 acres or if a fifth acre fixed plot size was chosen, only 10 plots would be needed. If the desired percent standard error is known, these methods can lead to too many or too few plots being measured. Too many plots increases the cost of the inventory unnecessarily, while too few plots may lead to higher than desired standard error for the variable of interest.

The prefered method to determine the number of plots is to use the sample size formula n =(T*CV%/%SE)^2, where T = student t-value with n-1 degrees of freedom and chosen alpha level, CV% = coefficient of variation for the variable of interest for plot size Pi, and %SE = desired percent standard error. The difficulty arises when obtaining an estimate for CV% since it changes with plot size. Estimates for CV% can be obtained from past data in the area, or from a reconnaissance cruise. The designer can pick the %SE which meets his end-use objective. The t-value has to be found through an iterative process because the sample size affects the t-value. The needed variables can be estimated with a minimal amount of work.

This formula is only an approximation due to the inherently unknown nature of CV% prior to actual sampling. An inaccurate estimate of CV% will yield a standard error too high or too low. The best strategy is to calculate the CV% after installing in a few plots. Using actual plot data permits reliable sample sizes to be calculated.

Different plot sizes will produce different variances in most stands. Bigger plot sizes should have smaller variances. This relationship is due to the fact that bigger plots account for more of the underlying spatial variation in the stand then smaller plots. Half of a large plot may be located in a clump and the other half in an opening.

Smaller plots are more likely to be either all in a clump or all in the open, so their variation from plot to plot will usually be higher. When estimating the number of plots using the sample size equation, large plot sizes (in general) will require fewer plots than plots of smaller size.

Optimization of plot size is important because of the potential for spending more time than is necessary to meet a given level of precision. The optimum plot size can be defined as the size that minimizes the total field sampling time required for a stated level of precision of the variable of interest (Zeide 1983). The elements that are needed to find the optimum plot size are estimates for the following two vectors: number of plots by plot size, and the total time required to measure plots by plot size. The total plot time equation is as follows:

$T_{plot} = n_i * (T_{baf} + T_{ht} + T_{dbh} + T_{travel})$

T_{plot} = total time needed to cruise the stand to meet a specified standard error.

n_i = the number of plots of size Pi that are required to meet given standard error.

T_{baf} = the time required to determine the number of "in-trees" of a variable-radius plot.

T_{ht} = the time required to measure a subsample of heights.

T_{dbh} = the time required to measure a given number of DBHs.

T_{travel} = the average time needed to travel from one plot to another.

An example stand was selected to illustrate this method for determining the optimal plot size and number of plots for a desired precision level. This stand was a 60 year-old pole size ponderosa pine and Douglas-fir mixed stand located at Lubrecht Experimental Forest. The average slope was 30%. The stand was originally clumpy and had been thinned to about 185 trees per acre resulting in a more uniform stand. Two sets of plots were taken, one before thinning and one after thinning.

Only eight randomly located plots were measured due to time limitations. A grid was placed over a map of the stand and pairs of x,y coordinates were randomly drawn. The plots were located on the ground using a Silva compass and a logger's tape. At each point, three (10, 20 and 40 basal area factor) plots were taken. The plots were remeasured after the thinning was completed.

The two sets of eight plots with 3 BAF's were processed through the INVTRY program (McQuillan et al. 1984) to obtain an estimate of the coefficient of variation for trees per acre (TPA) and total cubic foot volume per acre (CVTS). Tables 7.1 and 7.2 list the CV%, %SE and standard deviation (SD) for pre-thinning and post thinning conditions respectively.

Table 7.1

Pre-thinning CV% and %SE by BAF for CVTS and TPA

VARIABLE	BAF	CV%	%SE	SD
TPA	40	188.63	66.69	1040.5
TPA	20	98.80	34.93	667.2
TPA	10	80.86	28.59	474.6
CVTS	40	66.78	23.61	1479.1
CVTS	20	42.71	15.10	1221.0
CVTS	10	25.91	9.16	680.0

Table 7.2

Post Thinning CV% and %SE by BAF for CVTS and TPA

VARIABLE	BAF	CV%	%SE	SD
TPA	40	75.26	26.61	104.5
TPA	20	44.66	15.79	90.0
TPA	10	40.22	14.22	74.5
CVTS	40	54.50	19.27	923.0
CVTS	20	21.84	7.72	465.6
CVTS	10	22.63	8.00	434.9

The average number of "in" trees per plot by basal area factor (BAF) found for the pre- and post thinning stands are given in Table 7.3.

Table 7.3
Average Number of "in" Trees per Plot
by BAF and Treatment

Treatment	BAF	TREES
PRE	40	3
PRE	20	8
PRE	10	14
POST	40	2
POST	20	5
POST	10	9

The next step was to estimate the number of plots needed to meet a given standard error and alpha level. Four levels of percent standard errors were chosen: 10%, 15%, 20%, and 25%. Two alpha levels were considered .10 and .20 for all but the pre-thinning TPA, where the two alpha levels were .20 and .40. These higher alpha levels were picked due the high variability for TPA in the pre-thinning stand. Table 7.4 through 7.7 contain the estimated number of plots (n).

Table 7.4

Pre-thinning Number of Plots for TPA by BAF, %SE and Alpha Level

Alpha = .2

BAF	%SE 10	15	20	25
40	583	260	148	95
20	163	73	42	27
10	109	49	29	19

Alpha = .4

BAF	%SE 10	15	20	25
40	251	113	64	42
20	70	32	19	12
10	48	22	13	9

Table 7.5

Pre-thinning Number of Plots for CVTS by BAF, %SE and Alpha Level

Alpha = .1

BAF	%SE 10	15	20	25
40	123	56	33	22
20	51	24	15	10
10	20	10	7	5

Alpha = .4

BAF	%SE 10	15	20	25
40	75	34	20	13
20	32	15	9	7
10	13	7	5	4

Table 7.6
Post thinning Number of Plots for TPA
by BAF, %SE and Alpha Level

Alpha = .1

BAF	%SE 10	15	20	25
40	153	70	41	27
20	56	26	16	11
10	46	22	13	9

Alpha = .2

BAF	%SE 10	15	20	25
40	95	43	25	17
20	35	16	10	7
10	28	14	8	6

Table 7.7
Post thinning Number of Plots for CVTS
by BAF, %SE and Alpha Level

Alpha = .1

BAF	%SE 10	15	20	25
40	83	38	22	15
20	15	8	5	4
10	16	8	5	4

Alpha = .2

BAF	%SE 10	15	20	25
40	50	23	14	10
20	9	5	3	2
10	10	5	3	2

Once the number of plots has been estimated for each given alpha and error level combination, the amount of time required to move from plot to plot can be estimated. The travel time is estimated by multiplying the average distance between plots by the average speed. For systematic designs with n plots evenly distributed on a square lattice, the distance between the two nearest points can be calculated as follows: distance = (total area/n)^.5 (Zeide 1983). The same is true for the average minimum distance between points in random sampling (O'Regan and Arvanalitis 1965). The average speed used was .925 minutes (min.) per chain. This was from the time study reported in section I. The estimated total area was 300 square chains and the estimated travel distance between 2 adjacent plots was (300/n)^.5 * .925. The average time to travel between plots are located in Tables 7.8-7.11.

Table 7.8
Pre-thinning T_{travel} (min.) TPA
by BAF, %SE and Alpha Level

Alpha = .2

BAF	%SE 10	15	20	25
40	.66	.99	1.3	1.64
20	1.25	1.87	2.47	3.08
10	1.53	2.29	2.97	3.67

Alpha = .4

BAF	%SE 10	15	20	25
40	1.01	1.51	2.00	2.47
20	1.91	2.83	3.67	4.62
10	2.31	3.41	4.41	5.34

Table 7.9
Pre-thinning T_{travel} (min.) CVTS
by BAF, %SE and Alpha Level

Alpha = .1

BAF	%SE 10	15	20	25
40	1.45	2.14	2.79	3.42
20	2.24	3.27	4.14	5.07
10	3.58	5.07	6.06	7.17

Alpha = .2

BAF	%SE 10	15	20	25
40	1.85	2.75	3.58	4.44
20	2.24	3.27	4.14	5.07
10	4.44	5.07	6.06	7.17

Table 7.10
Post thinning T_{travel} (min.) TPA
by BAF, %SE and Alpha Level
Alpha = .1

BAF	%SE 10	15	20	25
40	1.30	1.91	2.50	3.08
20	2.14	3.14	4.05	4.83
10	2.36	3.42	4.44	5.34

Alpha = .2

BAF	%SE 10	15	20	25
40	1.64	2.44	3.20	3.89
20	2.71	4.01	5.07	6.06
10	3.03	4.28	5.66	6.54

Table 7.11
Post thinning T_{travel} (min.) CVTS
by BAF, %SE and Alpha Level

Alpha = .1

BAF	%SE 10	15	20	25
40	1.76	2.60	3.42	4.14
20	4.14	5.66	7.17	8.01
10	4.00	5.66	7.17	8.01

Alpha = .2

BAF	%SE 10	15	20	25
40	2.27	3.34	4.28	5.07
20	5.34	7.17	9.25	11.33
10	5.07	7.17	9.25	11.33

The next step was to use time estimating regression equations that were developed to estimate T_{baf}, T_{ht} and T_{dbh} (Tables 7.12 and 7.13, Wood 1984). These equations are:

$Ln(T_{baf})=.50712*(TRES\hat{}.5)+.00684*ASLP-.14959;$

$T_{dbh}=TRES*.2921;$

$Ln(T_{ht})=.453*Ln(TRES)+.292*(TRES\hat{}.5)+.0094*ASLP-.07485,$

where TRES is the number of trees on the plot, and ASLP is the average slope for the stand.

Table 7.12
Pre-thinning Stand Characteristics and Plot Time
by Measurement (min.)

BAF	TRES	ASLP	$T_{b}af$	$T_{d}bh$	$T_{h}t(all)$	$T_{h}t(opt)$
40	3.0	30	2.55	.88	3.35	1.58
20	8.13	30	4.49	2.37	7.29	2.98
10	14.0	30	7.05	4.09	12.96	4.41

Table 7.13
Post Thinning Stand Characteristics and Plot Time
by Measurement (min.)

BAF	TRES	ASLP	$T_{b}af$	$T_{d}bh$	$T_{h}t(all)$	$T_{h}t(opt)$
40	3.0	30	2.12	.55	2.83	1.20
20	8.13	30	3.19	1.39	5.46	2.10
10	14.0	30	4.64	2.48	8.80	3.08

The total time per plot ($T_{plot}=T_{baf}+T_{ht}+T_{dbh}$) was then calculated (Table 7.14).

Table 7.14
Total Time per Plot (min.)

Pre-thinning BAF	All Tres	Optimal	Post Thinning BAF	ALL Tress	Optimal
40	6.77	5.00	40	5.49	3.87
20	14.15	9.84	20	10.04	6.68
10	24.1	15.55	10	15.92	10.19

The last step was to add the between-plot travel time to the total time per plot and multiply this sum by the estimated number of plots, n. Tables 7.15 through 7.24 show the estimated total time in minutes for each BAF in each combination of alpha level and desired precision (percent standard error).

Table 7.15
Total Cruise Time Pre-thinning TPA All Trees
by BAF, %SE, and Alpha = .2 (min.)

BAF	%SE 10	15	20	25
40	4332.9	2018.1	1196.6	799.1
20	2510.0	1169.4	697.9	465.1
10	2794.1	1293.0	785.2	527.7

Table 7.16
Total Cruise Time Pre-thinning TPA All Trees
by BAF, %SE, and Alpha = .4 (min.)

BAF	%SE 10	15	20	25
40	1952.8	935.2	561.3	388.1
20	1124.1	543.2	338.6	225.2
10	1267.7	605.3	371.03	264.9

Table 7.17
Total Cruise Time Post thinning TPA All Trees
by BAF, %SE, and Alpha = .1 (min.)

BAF	%SE 10	15	20	25
40	1038.6	518.5	327.7	231.5
20	681.9	342.6	224.7	163.5
10	841.0	425.4	264.8	191.4

Table 7.18
Total Cruise Time Post Thinning TPA All Trees
by BAF, %SE, and Alpha = .2 (min.)

BAF	%SE 10	15	20	25
40	678.0	341.3	217.4	159.4
20	446.0	224.7	151.0	112.6
10	530.6	282.8	172.7	134.8

Table 7.19
Total Cruise Time Pre-thinning CVTS Optimal Ratio
by BAF, %SE, and Alpha = .1 (min.)

BAF	%SE 10	15	20	25
40	793.1	400.0	257.2	185.2
20	616.2	314.7	209.7	149.1
10	382.7	206.2	151.2	113.6

Table 7.20
Total Cruise Time Pre-thinning CVTS Optimal Ratio
by BAF, %SE, and Alpha = .2 (min.)

BAF	%SE 10	15	20	25
40	514.0	263.5	171.7	122.8
20	405.5	209.7	136.6	111.3
10	259.9	151.2	113.6	94.24

Table 7.21
Total Cruise Time Post thinning CVTS Optimal Ratio
by BAF, %SE, and Alpha = .1 (min.)

	%SE			
BAF	10	15	20	25
40	467.2	245.8	160.3	120.1
20	162.2	98.7	69.2	58.7
10	227.2	126.9	86.8	72.8

Table 7.22
Total Cruise Time Post Thinning CVTS Optimal Ratio
by BAF, %SE, and Alpha = .2 (min.)

	%SE			
BAF	10	15	20	25
40	306.8	165.9	114.1	89.4
20	108.1	69.2	47.8	36.0
10	152.6	86.8	58.3	43.1

Table 7.23
Total Cruise Time Pre-thinning TPA Optimal Ratio
by BAF, %SE, and Alpha = .1 (min.)

	%SE			
BAF	10	15	20	25
40	3303.5	1559.0	935.3	631.4
20	1808.4	855.1	517.1	348.9
10	1867.3	874.1	537.2	365.3

Table 7.24
Total Cruise Time Pre-thinning CVTS Optimal Ratio
by BAF, %SE and Alpha = .1 (min.)

	%SE			
BAF	10	15	20	25
40	1010.3	499.0	315.4	224.7
20	835.8	418.0	274.2	192.1
10	553.8	291.7	211.1	156.3

To use the results, one selects the appropriate table and column for desired %SE and then selects the BAF which minimizes total cruise time. One then uses the number of plots, n, already calculated for that BAF in that situation. For example, if you are interested in estimate TPA pre-thinning at an alpha level = .2 and % SE = 10 than the close-to-optimal BAF = 20 ft^2/acre (Table 7.15).

Discussion

Tables 7.1 and 7.2 reveal some interesting trends. The standard deviation for post thinning plot sizes based on a BAF of 10 ft^2/acre and 20 ft^2/acre for both TPA and CVTS are similar (90 vs 74.5 and 465 vs 435 respectively). This is probably due to the effect of thinning on the spatial distribution of a clumpy stand. The resulting distribution is much more uniform. One reason that the 40 ft^2/acre BAF is associated with a high CV and %SE is the low number of "in" trees per plot (1.875).

Another interesting trend is the difference in the estimate of coefficient of variation depending on whether the variable chosen is TPA or CVTS. The variation is greater for TPA than CVTS. This reinforces the notion that it is important to properly identify the variable of interest before planning the sampling design.

Tables 7.15 through 7.24 show the estimated total time to perform a stand cruise for given alpha levels and standard errors for situations involving measuring all the tree heights or for subsampling tree heights. The first two tables (7.15 & 7.16) show the estimated total cruising time for the pre-thinned stand with number of plots, n, based on the CV% for TPA at alpha levels of .20 and .40 respectively. In both cases a plot size of 20 ft²/acre BAF was found to be the best. This result does not change with %SE (10-25%). The difference between 10 ft²/acre BAF and 20 ft²/acre BAF plots was not as large as the difference between 40 ft²/acre BAF and each of the other two. It would clearly be a mistake to use a 40 ft²/acre BAF which would add almost twice as much time for sampling. This is caused by the large increase in the number of plots needed to meet the desired standard error.

Table 7.23 shows the effect of subsampling heights on the total time. The difference between the 10 ft²/acre BAF and the 20 ft²/acre BAF plots is even smaller than before but the optimal plot size was still 20 ft²/acre BAF. The only effect subsampling of heights had on the optimal size was to reduce the time differential between the 10 ft²/acre and 20 ft²/acre BAF size plots.

The next two tables (7.17 & 7.18) show the total cruise time based on CV% for TPA in the post thinning stand when all sample trees are measured. The outcome is the same, with the 20 ft²/acre BAF plot size being optimal. This result again does not change with %SE (10-25%). A mistake again would be to pick a 40 ft²/acre BAF, although the total time is less than the first because of the reduction in variation due to the thinning of the stand.

The next two tables (7.19 & 7.20) show the total cruise time required based on a subsample of heights and using a CV% calculated for CVTS. This time the 10 ft^2/acre BAF plot size is optimal. This result does not change with %SE (10-25%). The difference between the total time for sampling is fairly evenly spaced between the 10 ft^2/acre, 20 ft^2/acre and 40 ft^2/acre BAFs. This result is different from that in the first four tables and an obvious question is: "Is this caused by only subsampling the heights?" The answer is no. From the last table (7.24) one can see that the 10 ft^2/acre BAF is the best even when all the trees are measured. The difference lies in the choice of objective (CVTS instead of TPA).

Tables 7.21 and 7.22 are for post thinning total time based on a subsample of heights for CVTS. These results show that a 20 ft^2/acre BAF is the best, and this result does not change with %SE (10-25%). Once again the 10 ft^2/acre BAF and 20 ft^2/acre BAF are closer together than the 40 ft^2/acre BAF.

In this situation the conclusions that can be drawn are: If the target of interest is CVTS then the optimal BAF is 10 ft^2/acre regardless of %SE or alpha level, and if the target of interest is TPA then the optimal BAF is 20 ft^2/acre, again regardless of %SE or alpha level. Subsampling of heights was found to have no effect on optimal plot size.

This is an example of the kind of analysis that can be done to reduce stand inventory costs. The effects of sampling thinned and unthinned stands has been demonstrated, and the impact of the choice of variable of interest on the total of time to cruise an area to a given precision level at optimal configuration has been shown. A very general conclusion is that although it may take longer to measure a larger plot, the smaller variance associated with larger plots compensates because fewer plots are required. This methodology for determining the optimal number of plots concurrently with optimal plot size for minimizing cruising costs (under desired levels of precision) could be built into a simple computer program for use as an aid in cruise design.

SECTION III

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be drawn. Much time can be saved by properly planning a timber inventory. This planning process includes defining the objectives of the end users. Managers at different levels in the organization require different types of information and have different precision standards. The user with the most information needs and highest precision standards has the most impact on the inventory costs. One obvious fact is that a single standard inventory technique, applied under all conditions is not likely to be cost efficient most of the time. To allow partial optimization of inventory design, a key could be made for different information needs and stand conditions such as stand age, size, species composition and possible silvicultural alternatives. As the range of possible stand treatments increases, the amount of information collected and the standard of accuracy should probably increase also. But common sense should prevail. For example, if the stand is stagnating old growth lodgepole pine does one really need to determine the age of all the growth sample trees?

As a matter of policy, some basic guidelines need to be generated for determining appropriate accuracy standards, because strict standards unnecessarily increase the total time and cost of the inventory. Estimating diameters and heights with competent crews has been found to have no effect on CVTS per acre or TPA estimates. How high do the accuracy standards for DBH and height need to be? This is one area that needs more research.

The time break-down for various measurements can give inventory planners some idea of what percent of the total time a variable requires. The measurement which requires the most time is height. This variable is most commonly subsampled. If the optimal ratio of DBH-to-heights is calculated, the time to measure the "in" trees on the plot becomes the most time-consuming variable. The time-consuming part of this measurement is measuring borderline trees. Nevertheless, I would recommend measuring borderline trees for two reasons: first, people see borderline trees differently so the bias due to combining cruise data from a couple of crews is unknown and secondly, the circumference of a tree may not be circular. The diameter may be more or less than viewed in the relaskop or the prism, therefore, its limiting distance should be checked. The amount of time that is needed to travel between plots becomes the most important percentage of the total time when the distance between plots exceeds approximately six chains.

Estimation of diameters and heights has been demonstrated to reduce total sampling time and still give accurate estimates for total TPA and CVTS per acre. The advantage of estimating all heights over measuring using the optimal ratio of DBHs to heights is questionable for second growth stands. The best procedure for second growth may be to measure one tree per plot and estimate the remaining trees that can be seen without going out of one s way. This inventory design is best for extracting information for either planning silvicultural treatments or for long-term planning. There are some rules-of-thumb that should be applied if this estimation procedure is used. The cruiser should start each day with estimating and measuring a sample of trees. If the site conditions change appreciably, the cruiser should measure a couple of samples to check himself/herself.

The optimal ratio of DBHs-to-height has been calculated for the eight study stands. A general rule for the ratio of DBHs-to-height measurements would be 3:1 for old growth and 4:1 for second growth. If the stand is second growth and has a low CV% for height then I recommend a ratio of either 5:1 or 6:1. If the stand is uneven-aged I recommend reducing the ratio to 2:1 because of the high variation of tarif in uneven aged stands.

The Bootstrap technique was introduced for estimating the standard error of an estimator whose variance formula cannot be derived from theory. This procedure can be applied to complex estimators. The important theme is the substitution of raw computing power for theoretical analysis (Efron and Gong 1983).

I found the comparison of the four different sampling designs to be little surprising, in that 3P sampling was not found to be unequivocally superior. The optimal plot sampling method proved superior for most of the second growth stands, while the Plot 3P-ht and Ind. 3P-ht techniques were best in the old growth stands. Based on these results, I would recommend using the optimal plot technique for second growth stands. In sampling old growth stands I would just estimate heights of the "in" trees. Because of the preparation time for and complexity of 3P sampling and its mixed results.

And last, the importance of using the proper plot size was also demonstrated. The plot size needs to be large enough so that trees will be sampled without large variation in the count of "in" trees. For most situations using plot sizes that yield less than three or four "in" trees per plot is not efficient. (One factor that has not been considered is the effect of increasing measurement error when determining the number of "in" trees on a larger plot size).

<u>Specific Recommendations</u>

1) Before planning an inventory, decide what is the measure of interest (eg. TPA or CVTS per acre) and what precision level (in terms of %SE) is desired.

2) Do not use 3P-sampling in most instances.

3) Subsample tree heights using a ratio of between 2 and 6 DBH measurements to each height measurement. Heights should be measured more frequently (ratio of 2 or 3 to 1) when stands are heterogeneous

and less frequently (ratio of 5 or 6 to 1) when stands tend to homogeneity.

4) Use ocular estimation for both DBH and height measurements with well-trained or experienced field personnel. Personnel should check their estimation accuracy by regular verification, especially when stand conditions change.

5) Select a BAF that seldom yields fewer than 4 "in" trees per plot. Use a pre-cruise trial to determine this BAF if necessary.

6) Use the sample size estimation formula to determine the desired number of plots appropriate to the selected BAF. Again if necessary, conduct a pre-cruise trial to estimate CV%.

7) When the inventory project is sufficiently large, use time and motion study techniques to determine the times for various plot procedures and travel time, and use these relationships to determine the optimal (cost minimizing) combination of BAF and number of plots as described in chapter 7.

8) For smaller projects, use a key or set of guidelines to customize inventory design to the stand conditions involved.

APPENDIX A

DESCRIPTION OF STANDS

This study utilized 8 stands in western Montana selected to represent 3 identified stand types. The types were (1) Old Growth, (2) Pole, and Immature Saw Timber. This appendix describes the sampled stands.

Old Growth - The two old growth stands selected were located in Section 31, T.13 N., R.14W., MPM.. The two stands were significantly different. Stand OLD GR. #1 is located in the north east corner of the section. The aspect is south to southwest. The average slope is 38% with a range of 28% to 51%. The north end of the stand is approximately midslope. The south border is located at the bottom of a small drainage. The topography of the stand is primarily convex with a few small undulations.

The species composition is Douglas-fir (*Pseudotsuga mensiesii*) and a few ponderosa pine (*Pinus ponderosa*). This stand has a few small clumps of dense pole sized Douglas-fir. Most of the trees over 5 inches DBH are over 100 years old. The bigger trees, 15 inches and greater, are more than 170 years old.

The understory is composed of pine grass, elk sedge, snowberry, balsamroot, huckleberry and twin flower. The two most common habitat types are PSME/LIBO and PSME/SYAL (Pfister et al. 1977). The stand does not have much brush. The understory vegetation does not impede movement. The fuel loading is low, and a high percentage of the load is in the heavy fuels. There are only a few scarred blown down trees.

Stand OLD GR.#2 is located on the south side of Section 31, T.13 N.,R.14 W., MPM. The aspect is north. The average slope is 42% with a range from 36% to 49%. Stand OLD GR. #2 starts in a stream bottom and proceeds to midslope. The topography of the stand is convex with a few benches.

This is a two-storied mixed species stand. The species composition expressed as a percent of CVTS is the following: Douglas-fir (32.6%), western larch _(Larix occidentalis)_ (8.8%), Engelmann spruce _(Pices engelmann)_ (11.3%), lodgepole pine _(Pinus contorta)_ (44.3%) and subalpine fir _(Abies lasiocarpa)_ (2.9%). The lodgepole pine is mature and dying. There is regeneration of all species present except lodgepole pine. The overstory trees are approximately 170+ years old and the understory trees are approximately 70 years old.

The habitat type for the stand is ABLA/MEFE. The ground vegetation is made up of the following menziesia _(Menziesia ferruginea)_, alder _(Alnus sinuata)_, huckleberry _(Vaccinium gloulare)_, arnica _(Arnica coridfolia)_, twin flower _(Linnaea borealis)_, elk sedge _(Carex geyeri)_, pinegrass _(Calamagrositis rubescens)_, and some beargrass _(Xerophylum tenex)_. The brush is dense in this stand and made movement difficult.

The fuel loading is high. There is a lot of fallen lodgepole pine which also impedes travel.

Pole Size - The sole pole stand, Pole #1, is located south of the Garnet road approximately 5 miles from Highway 200 in Sec. 24, T.13 N., R.14. W., MPM. The aspect of this stand is north to northwest. The average slope is 16.7% with a range of 10% - 25%. The stand starts near the bottom of a small drainage and continues to the top of the slope. The topography of the stand is convex.

Stand Pole #1 composition is primarily lodgepole pine with secondary components of Douglas-fir and western larch. This is a one storied stand. The regeneration is mostly Douglas-fir. The lodgepole pine is mostly 65 years old. The few big larch and Douglas-fir are over 120 years old.

The most common habitat type is PSME/LIBO. The undergrowth vegetation height is between 1-3 feet. Ground cover consists of twin flower, arnica, huckleberry, grouse whortleberry, beargrass, oregon grape, kinnickinnick, spirea and scattered menziesia and alder. The brush is only moderately dense and does not affect movement to any large degree. Fuel loading is low, and there are not many fallen trees.

Immature Saw Timber - The immature stands were divided into two subgroups: stands that had been entered within the last 50 years (managed) and those that had not (unmanaged). Three out of the five stands fell into the managed class (IM. SW. #1, IM. SW. #2 and IM. SW. #3) and two fell into the unmanaged class (IM. SW. #4 and IM. SW. #5).

Stand IM. SW. #1 is located near Lubrecht Forest on State land just west of Highway 200 in Sec. 36, T.14 N., R.15 W., MPM. The average slope is 10% with a range from 7% - 20%. The predominant aspect is north to northwest. The stand is located midslope and topography is convex.

Stand IM. SW. #1 is single storied and was thinned about 15 years ago. The primary tree species are ponderosa pine (38.1%), Douglas-fir (45.1%) and western larch (16.2%). In the openings there is excellent regeneration of ponderosa pine. The average age of this stand is between 80-90 years old. There are a few big trees (dbhs over 22 inches) over 150 years old.

The most common habitat type is PSME/SYSL. There is not much ground cover except for snowberry, spirea, pine grass and elk sedge. There is thinning slash in some areas but the depth is low enough not to affect movement.

Stand IM. SW. #2 is located north off of the Baker road in Sec. 11, T.14 N., R.15 W., MPM. The aspect is mainly from the east. The average slope is 6.7% with a range from 6% - 20%. This stand is located midslope and the topography is convex. The primary tree species is ponderosa pine (59.5%), with Douglas-fir (27.7%) and western larch (12.4%). The average age of the stand is about 80 years old. There is very little regeneration.

The most common habitat type is PSME/SYAL. The ground cover is made up of spirea, snowberry, pinegrass, elk sedge and kinnikinnick. The fuel load is very low because the stand was whole tree thinned for hog fuel in 1983.

The last three stands are located on Champion land. Stands IM. SW. #4 and IM. SW #5 have not been entered since their first harvest about 80 years ago. Stand IM. SW. #3 was cut in the last 10 years.

Stand IM. SW. #3 is located off the Twin Creeks logging road in Sec. 27, T.14 N., R.17 W., MPM. The average slope is 12.1% with a range from 7% - 26%. This stand is located about midslope. The major aspect is south and the topography is convex.

Spatial distribution in this stand is clumpy. The species by percent of cubic foot volume are 88.7% ponderosa pine, 9.2% Douglas-fir, 0.8% western larch and 1.3% lodgepole pine. Clumps of ponderosa pine and Douglas-fir regeneration can be found throughout the stand. This stand was selectively logged approximately 10 years ago. The most common habitat is PSME/CAGE. The brush does not affect movement through the stand. Fuel loading is moderate.

Stand IM. SW. #4 is located off the Twin Creeks road in Sec. 27, T.14 N., R.17 W., MPM. The average slope is 17% with a range of 14% - 36% with a south aspect. This stand starts at the lower slope and ends at the midslope. It is a second growth stand that looks somewhat understocked. Ponderosa pine makes up 57.6% of the cubic foot volume, while Douglas-fir has 22.4%, western larch has 11.7% and lodgepole pine 8.2%. The most common habitat type is PSME/VACA.

Stand IM. SW. #5 is also located off the Twin Creeks road in Sec. 27, T.14 N., R.17 W., MPM. The average slope is 25% with a range from 15% to 36%. The predominant aspect is northeast. The stand starts about two chains above a stream and proceeds to midslope. The stand has some benches but its topography is mostly convex.

This is a two-storied stand. One story consists of large Douglas-fir and western larch. These trees are each over 150 cubic feet in volume. The main story consists of western larch (62.6%) with secondary species being Douglas-fir (22.0%) and ponderosa pine (15.4%). The average stand age is less than 80 years old. There is very little regeneration.

The most common habitat type is ABLA/LIBO. The ground vegetation is made up of huckleberry, alder, mountain maple, spirea, arnica, twinflower and beargrass. The brush is moderate and does impede movement. The fuel loading is low.

APPENDIX B

Summary of Results by Stand and Method

OLD GROWTH SOUTH #1
SUMMARY TABLE B.1
TIME AND STANDARD ERRORS BY METHOD
6 PLOTS

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	83.77	8.041	4877.09	738.78	138.5	41.93
PLOT 3P-HT	85.35	9.204	5507.02	545.66	278.3	83.88
IND. 3P-HT	95.78	9.607	5544.8	681.22	369.9	143.91
OPTM. PLOT R.	80.29	7.062	5116.9	648.12	369.9	143.91
TOTAL PLOT	122.1	12.223	5477.67	675.4	369.9	143.91

OLD GROWTH #2
SUMMARY TABLE B.2
TIME AND STANDARD ERRORS BY METHOD
8 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	112.72	3.819	3162.89	506.69	156.3	40.26
PLOT 3P-HT	118.5	6.915	3476.5	382.66	277.2	54.75
IND. 3P-HT	125.18	7.288	3655.9	356.6	453.8	76.10
OPTM. PLOT R.	101.72	4.028	3331.4	432.11	453.8	76.10
TOTAL PLOT	140.60	5.564	3613.93	460.05	453.8	76.10

POLE #1
SUMMARY TABLE B.3
TIME AND STANDARD ERRORS BY METHOD
10 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	111.75	5.914	3183.58	340.03	543.7	125.16
PLOT 3P-HT	117.10	11.146	3434.82	351.74	705.6	144.73
IND. 3P-HT	125.30	10.616	3405.0	367.36	731.8	127.08
OPTM. PLOT R.	86.96	6.25	3373.4	343.39	731.8	127.08
TOTAL PLOT	136.95	8.362	3384.67	375.36	731.8	127.08

IM.SW.#1
SUMMARY TABLE B.4
TIME AND STANDARD ERRORS BY METHOD
22 PLots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	211.93	14.84	2348.91	210.56	257.7	35.22
PLOT 3P-HT	208.27	16.510	1845.69	195.86	134.5	29.11
IND. 3P-HT	245.3	19.320	1848.2	196.02	145.5	18.68
OPTM. PLOT R.	224.10	15.966	1680.9	183.10	145.5	18.68
TOTAL PLOT	320.13	30.751	1809.62	199.96	145.5	18.68

IM.SW.#2
SUMMARY TABLE B.5
TIME AND STANDARD ERRORS BY METHOD
14 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	138.08	9.389	2894.39	236.87	156.3	17.55
PLOT 3P-HT	156.97	10.924	2601.20	177.41	118.4	10.86
IND. 3P-HT	181.87	11.41	2614.00	228.26	161.5	14.37
OPTM. PLOT R.	162.47	9.762	25558.3	178.29	161.5	14.37
TOTAL PLOT	228.87	14.551	2577.69	191.06	161.5	14.37

IM.SW #3
SUMMARY TABLE B.6
TIME AND STANDARD ERRORS BY METHOD
14 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	121.62	11.348	1488.06	217.87	98.3	21.17
PLOT 3P-HT	100.80	10.346	1707.71	267.72	101.0	25.19
IND. 3P-HT	116.95	11.56	1729.7	275.92	150.8	30.79
OPTM. PLT R.	107.53	10.102	1503.90	235.27	150.8	30.79
TOTAL PLOT	147.02	14.896	1531.35	239.96	150.8	30.79

IM.SW.#4
SUMMARY TABLE B.7
TIME AND STANDARD ERRORS BY METHOD
9 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	59.77	5.01	2673.25	346.1	77.05	76.11
PLOT 3P-HT	75.98	3.844	2681.44	212.09	87.61	86.91
IND. 3P-HT	82.48	4.059	2749.6	199.16	125.6	39.76
OPTM. PLOT R.	63.39	2.999	2615.1	216.74	125.6	39.76
TOTAL PLOT	88.42	4.644	2645.4	210.59	125.6	39.76

IM.SW.#5
SUMMARY TABLE B.8
TIME AND STANDARD ERRORS BY METHOD
12 Plots

METHOD	T.TIME	SEtim	CVTS	SEcv	TPA	SEtpa
PLOT 3P-CV	159.53	10.659	4424.56	453.43	224.2	56.18
PLOT 3P-HT	135.60	8.712	4601.85	421.04	351.2	126.95
IND. 3P-HT	152.57	9.644	4691.80	562.22	335.5	62.54
OPTM. PLOT R.	127.28	7.329	4754.8	406.22	335.5	62.54
TOTAL PLOT	186.53	14.916	4790.07	414.82	335.5	62.54

APPENDIX C

DERIVATION OF RATIO EQUATION FOR BALANCE OF MEASUREMENTS

The derivation of the optimal diameter-to-height is as follows;

The equation for total time on a plot is:

$T_{tot}=(n_{dbh})*(T_{dbh})+(T_{ht})*(n_{ht})$

where:

T_{tot} = total time,

T_{dbh} = average time per dbh measurement,

n_{dbh} = number of DBH sampled,

T_{ht} = average time per height measurement,

n_{ht} = number of heights sampled.

The next step is to estimate the variance for individual tree volume. Due to the fact that the function V = g(ht,dbh) (where V=volume of a tree) is not a linear relationship. Therefore the relationship of var(V) = var(ht) + var(dbh) + 2cov(ht,dbh) can not be used. The variance of volume of a tree can be approximated by considering a Taylor expansion of the function g(ht,dbh) In general for $Y= g(X_1,X_2,\ldots,X_n)$, we assume that each X_i has a mean V_i and $var(X_i)$. By expanding $g(X_1,X_2,\ldots,X_n)$ around the point $(V_1,V_2,\ldots,V_n)$ and ignoring higher-order terms:

$Y=g(V_1,V_2,\ldots,V_n)+(X_1-V_1)*[\partial g/\partial gX_1 |_{(v_1,\ldots,v_n)} +\ldots$

$+ X_n \; V_n) * [\partial g/\partial X_n |_{(v_1,\ldots,v_n)}]$ (Larsen and Marx 1981) (1)

therefore,

$$Var(Y)=Var(g(V_1,V_2,...,V_n) + [\partial g/\partial X_1 |_{v_1,...,v_n}]\hat{}2*$$
$$Var(X_1-V_1) +...+[\partial g/\partial X_1 |_{v_1,...,v_n}]\hat{}2*$$
$$Var(X_n-V_n) + 2*[\partial g/\partial X_i |_{v_1,...,v_n}]*$$
$$[\partial g/\partial X_j |_{v_1,...,v_n}]*Cov(X_i,X_j), \quad (2)$$

where Var is the variance, SD is the standard derivation and r(Xi,Xj) is the correlation coefficient. $g(V_1,V_2,...,V_n)$ and $(V_1,V_2,...,V_n)$ are constants so their variance equals 0, and $cov(X_i,X_j)$ = $r(X_i,X_j)*SD(X_i)*SD(Xj)$.

$$Var(Y)=[\partial g/\partial X_1 \,_{(v_1,...,v_n)}]\hat{}2*Var(X_1)+...+[\partial g/\partial X_n |_{v_1,...,v_n}]\hat{}2$$
$$*Var(X_n)+2*[\partial g/\partial X_i |_{v_1,...,v_n}]*[\partial g/\partial Xj |_{v_1,...,v_n}]\hat{}2$$
$$r(X_i,X_j)*SD(X_i)*SD(X_j) \quad (3)$$

The volume equation used for total cubic feet was, V=10^A*DBH^B*HT^c (Champion 1976) where A, B, and C are constants dependent on age and species, DBH is diameter at breast height, and HT is total height of the tree. The partial derivatives are:

$$\partial V/\partial DBH = 10\hat{}A*B*DBH\hat{}(B-1)*HT\hat{}C \quad (4)$$

and $$\partial V/\partial HT = 10\hat{}A*C*DBH\hat{}B*HT\hat{}(C-1) \quad (5)$$

Applying equation 3 we will get:

$$Var(V)=(\partial V/\partial DBH)\hat{}2*Var(DBH)+(\partial V/\partial HT)\hat{}2*Var(HT)+$$
$$2*B*C*(\partial V/\partial DBH)*(\partial V/\partial HT)*r(DBH,HT)*SD(DBH)*SD(HT) \quad (6)$$

Hence we can express the square of SE(V) as:

$$[SE(V)]\hat{}2=(\partial V/\partial DBH)\hat{}2*Var(DBH)/n_{dbh}+(\partial V/\partial HT)\hat{}2*Var(ht)/n_{ht}+$$
$$2*B*C*(\partial V/\partial DBH)*(\partial V/\partial HT)*r(DBH,HT)*$$
$$SD(DBH)*SD(HT)/(n_{dbh}\hat{}.5*n_{ht}\hat{}.5) \quad (7)$$

DBH and HT are the arithmetic mean height and diameter respectively, and r(DBH,HT)is the correlation coefficient. The total time equation is solved for n_{ht}.

$$n_{ht} = (T_{tot} - T_{dbh} * n_{dbh}) / T_{ht}$$

Substituting the last expression into equation 7 and setting its first derivative with respect to n_{dbh} equal to zero (equation 9), one finds numerically the n_{dbh} which corresponds to the minimum standard error of volume (Zeide 1984).

$$\begin{aligned}[SE(V)]^{2} = {} & (\partial V/\partial DBH)^{2} * Var(DBH)/n_{dbh} + (\partial V/\partial HT)^{2} * \\ & Var(HT) * T_{ht}/(T_{tot} - n_{dbh} * T_{dbh}) + 2*B*C(\partial V/\partial DBH) * (\partial V/\partial HT) * \\ & R(DBH,HT) * (SD(DBH)/n_{dbh}^{.5}) * SD(HT) * [T_{ht}/(T_{tot} - Td_{bh} * n_{dbh})]^{.5} \quad (8)\end{aligned}$$

$$\begin{aligned}dV/dn_{dbh} = {} & (-1) * (\partial V/\partial DBH)^{2} * Var(DBH)/n_{dbh}^{2} + (\partial V/\partial HT)^{2} * \\ & Var(HT) * T_{ht} * T_{dbh}/(T_{tot} - n_{dbh}) + 2*B*C*(\partial V/\partial DBH) * (\partial V/\partial HT) * \\ & r(DBH,HT) * [-.5 * SD(DBH) * SD(HT) * T_{ht}^{.5}/n_{dbh}^{1.5}) * (T_{tot} - T_{dbh} * n_{dbh})^{-.5} + \\ & .5 * SD(HT) * SD(DBH) * T_{ht}^{.5} * Td_{bh}/n_{dbh}^{.5} * (T_{tot} - T_{dbh} * n_{dbh})^{-1.5}] \quad (9)\end{aligned}$$

LITERATURE CITED

Arvanitis, L.G.and R.Newton. 1965. Plot sizes for timber cruising in Georgia. J. For. 63(12):930-932

Bonner, G.M. 1972. A test of 3P sampling in forest inventories. For. Sci. 18(13):198-202 p.

Chehock, C.R. 1982. Timber volume determination with multi-stage sampling.The application of 3P sampling and STXMOD program. Tech. Pub. SA-TP-19. 1982. 135 pp. U.S.D.A., For SERV. southeastern area.

Diaconis, P.and Efron,Bradly. Computer-intensive methods in Statistics. Sci. Am. 249(1):116-130

Dilworth, J.Richard and John F.Bell.1972. Variable probability sampling - variable plot and three-P. Ore. State Univ. Bookstores, Inc. Corvallis, Ore. 129 pp.

Efron, B. 1982. The Jackknife, the bootstrap, and other re-sampling plans. CBMS-NSF Regional Conference Series in Applied Mathematics.

------------and Gail Gong. 1983. A leisurely look at the Bootstrap, the jackknife, and Cross-validation. American Stat. vol 37, no.1. 36-48

Freese, F. 1962. Elementary forest sampling. U.S.D.A. Agric. Handb. 232, 91 pp.

Gertner, George Z. 1984. Control of sampling error and measurement error in a horizontal point cruise. Can. J. For. Res. 14:40-43

Gregoire, Timothy G. 1984. The jackknife: an introduction with applications in forestry data analysis. Can. J. For. Res. Vol. 14. 493-497

Grosenbaugh, L.R. 1964. Some suggestions for better sample-tree measurement. Soc. Am. For. Proc. Oct.20-23, 1963 Boston, Mass.34-42

------------. 1965. Three-P sampling theory and program THRP for computer generation of selected criteria. U.S. For. Ser. Res. Pap. PSW-21. 53 pp.

------------.1971. STX-1-11-71 for dendrometry of multistage 3P estimates. U.S. Dep. Agric., For. Ser. 63 pp.

------------.1976.Approximate sampling variance of adjusted 3P estimated. For. Sci. 22(2):173-176

------------ and W.S.Stover. 1957. Point-sampling compared with plot-sampling in southwest Texas. For. Sci. 3(1):2-14

Hartman, George B. 1967. Some practical experience with 3P sampling and the Barr and Stroud dendrometer in timber sales cruising. J. For. 70(9):566-568

Larhiri, D.B. 1975. Three-p sampling an annotated bibliography. U.S.D.A. For. Ser., Northeast Area, State and Private For., Upper Darby, Penn., 25 pp.

Larsen, Richard, J. and Morris L. Marx. 1981. <u>An Introduction to Mathematical Statistics and its Applications</u>. Prentice-Hall, Inc., Englwood Cliffs, N.J.

Lund, H.Gyde. 1975. Three-P or not. Resource Inventory notes, BLM-1, U.S.D.I., BLM.3 pp.

McQuillan A., Peter Sawyer, Jean Boal, William Wood, Gary D. Ullman and Hans R.Zuuring. 1984. INVTRY: A system of generalized timber stand inventory programs for use in Montana and the Northern Rocky Mountains. School of Forestry, U of Montana, Missoula, Mt.

Mesavage, C.and L. R. Grosenbaugh. 1956. Efficiency of several cruising design on small tracts in Northern Arkansas. J. For. 54(99): 569-576

Miller, R. G. 1974. The jackknife - a review. Biometrika, 61: 1-15

O'Regan G.William. 1966. Cost-effectiveness in Forest Sampling. For. Sci. 12(4): 406-414

Pfister, R.D., B.L.Kolvalchik, S.F.Arno and R.C.Presby.1977 Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34, Intermt. For. and Range Exp. Stn., Ogden, Utah. 174 pp.

Reinhardt, Howard E. and Don O. Loftsgaarden. 1977. <u>Elementary Probability and Statistical Reasoning</u>. D.C Heath and Company. pg 417

Rennie, J.C. 1976. Point 3P sampling: A useful timber inventory design. For. Chron. June 1976:145-146

Schreuder, Hans T., Joseph Sedransk and Kenneth D Ware. 1968. 3p sampling and some alternatives, 1. For. Sci. 14 (40):429-453

-----------, Joseph Sedransk and Kenneth D Ware. 1971. 3p sampling and some alternatives, 2. For. Sci. 17(10):103-453

-----------.1976. Comment by Hans T.Schreuder note by L.R. Grosenbaugh, Approximate sampling variance of adjusted 3P estimates. For. Sci. 22(2):176

Sharpnack, David A. 1965. A computer trial of 3P sampling Soc. Am. For. Proc. 1964:225-226

Smith, S. H. 1981. In-place information needs for activity planning in forestry. In, In-place resource inventories: principles and practice. Proc. of a national workshop. Bangor, Maine. pp. 39-42.

Space, James C. 1971. Three P cruise your next timber sale. The consultant. 18(3): pp. 64-68

Turman, D. J. 1970. Field test of the STX system. File 2440, U.S. Dep. Agric. For. Serv. Region One, Missoula Mt. File 2440, Jan.30, 12 pp.

Van Hooser, Dwane D. 1974. Inventory remeasurement with two-stage 3P sampling. In Inventory design and analysis, p.53-62 Ed. W. E Frayer, Geogre B.Hartman and David R.Bower, Soc. Am. For., Wash. D. C.

Waint, Harry V., Jr. 1974. Combine 3p and point sampling for efficient cruising. For. Notes 2:12-15 W. Va. Univ., Morgantown, W., Va.

-----------. 1976. Elementary 3P sampling. W. Va. Univ., Morgantown, W. VA., 45 pp.

Wood, William L. 1984 . Unpublished work. University of Montana, School of Forestry, Missoula, MT.

Zeide, Boris. 1983. Balance of measurements. Renwable Resource Inventories for Montoring Changes and Trends. An International Conference, Corvallis, Or. Aug 15-19 1985. 185-187 pp.